Real-Time Small Signal Stability Assessment of the Power Electronic-Based Components in Contemporary Distribution Systems

M. Amin Salmani
REAL-TIME SMALL SIGNAL STABILITY ASSESSMENT OF THE POWER
ELECTRONIC-BASED COMPONENTS IN CONTEMPORARY DISTRIBUTION SYSTEMS

By

M. AMIN SALMANI

A Dissertation submitted to the Department of Electrical and Computer Engineering in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Degree Awarded:
Fall Semester, 2014
Mohamadamin Salmani defended this dissertation on August 22, 2014.
The members of the committee were:

Chris S. Edrington  
Professor Directing Dissertation

Juan Ordonez  
University Representative

Petru Andrei  
Committee Member

Simon Foo  
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the dissertation has been approved in accordance with university requirements.
بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

In the name of God Almighty, the Most Compassionate, the Most Merciful

This is by the grace of my God [Quran]

I dedicate this dissertation to my family: my reason to live and move forward. A special feeling of gratitude to…

My true soul mate, my peace, my love, and my life partner Zoya, who has never stopped supporting, encouraging, loving, and believing in me and who has never left my side;

My loving, sympathetic, and compassionate parents, Dr. Soheila Jadidid and Dr. Ali Salmani, who are the foundation of the family and for their endless love, support and encouragement;

My loving and caring sister Soudeh, for being considerate and supportive;

My responsible, gentle, and warm-hearted brother Hosein, for taking care of the most important part of my life, my brother Ilia, in my absence and preserving, protecting, and supporting the family.
ACKNOWLEDGMENTS

I would never have been able to make it to this point and finish my dissertation without the guidance of my committee members, support from my family, and help from friends.

Firstly, I would like to express my deepest gratitude to my advisor, Dr. Chris Edrington, for the opportunity he gave me to complete this work and his excellent guidance, caring, patience, and providing me with an excellent atmosphere along the way. I benefited greatly from his experience, and his vision was instrumental in developing this research. I deeply appreciate all the opportunities he gave me to grow and learn as an engineer over the last three years, and for him continually challenging me to better the quality of my work.

I would also like to thank Dr. Simon Foo, Dr. Petru Andrei, and Dr. Juan Ordonez, my PhD committee members, for consulting me and guiding my research for the past several years and helping me to develop my background in electrical engineering. Their comments and supports were greatly appreciated.

A very special thanks to my dearest friend Chris Widener, who as a real mate was always willing to help and give his best suggestions and advices. Many thanks for reviewing and revising this dissertation for me.

I thank my all colleagues at the Center for Advanced Power Systems for their time, assistance, and friendship during this project: Jesse Leonard for assisting me in developing the hardware experiment of this work and for allowing me to bounce ideas off of him and keeping me on the right path by questioning/criticizing me; Isaac Leonard for always answering my questions with open arms, for his patient understandable explanations and for his invaluable expertise in power systems modeling and simulation; Harsha Ravindra for his expertise in power system modeling and his help with RSCAD modeling, and Fletcher Fleming for encouraging me and keeping me motivated.

I would like to thank my group-mates at the Energy Conversion and Integration Thrust group, who have always constructively criticized my work and assisted me to enhance the quality of my work.
I would also like to acknowledge the ERC Program of the National Science Foundation (FREEDM Systems) for supporting this work under Award Number EEC-0812121.

For my brothers and sister: Hosein, Ilia, and Soudeh who are the most important people in the world for me.

To my dad, Dr. Ali Salmani for being the most loving father, best role model, and for keep motivating and supporting me in all my decisions from my very early days. Thank you for all the sacrifices you have made and for everything you provided me.

To my mom, Dr. Soheila Jadidi, who has always believed in me, encouraged, supported, and loved me every step of my life journey. Her endlessly loving heart allowed me to become the person that I am today. I love you, mom!

Lastly and most importantly, I would like to give special thanks and love to my life partner and my soul mate, Zoya, who has always stood by my side, believed in me, supported me, helped me, and cheered me up through the good days and bad days of these years. I love you, Zoya!
# TABLE OF CONTENTS

LIST OF FIGURES ....................................................................................................................... ix
LIST OF TABLES .......................................................................................................................... xiii
LIST OF ABBREVIATIONS ........................................................................................................ xiv
ABSTRACT ................................................................................................................................... xvi

CHAPTER 1 ....................................................................................................................................1

INTRODUCTION .......................................................................................................................... 1
  1.1 Motivation and goal ......................................................................................................... 1
  1.2 State of the art .................................................................................................................. 2
  1.3 Contribution ..................................................................................................................... 6

CHAPTER 2 ....................................................................................................................................7

GENERAL REQUIREMENTS FOR SMALL-SIGNAL STABILITY ASSESSMENT ............... 7
  2.1 Negative impedance and dynamics of the PEDS under active loads ......................... 7
  2.2 Generalized Nyquist Criterion ....................................................................................... 8
    2.2.1 Generalized Nyquist evaluation ................................................................................ 9
    2.2.2 The Nyquist impedance-admittance (immittance) criterion ................................... 10
  2.3 Small-signal impedance measurement techniques ......................................................... 11
    2.3.1 Impedance measurement at DC interface of a PEC ................................................ 12
    2.3.2 Impedance measurement at AC interface of a PEC ................................................ 12
    2.3.3 Impedance measurement for high power factor rectifiers ...................................... 15
  2.4 Ideally balanced injection in impedance measurement techniques ................................ 16
  2.5 Source impedance/load admittance matrix realizations ................................................ 18

CHAPTER 3 ..................................................................................................................................21

DIFFERENT SMALL-SIGNAL STABILITY ANALYSIS TECHNIQUES ............................... 21
  3.1 Generalized immittance-based techniques ................................................................. 21
  3.2 Numerical and computational-based techniques ......................................................... 23
    3.2.1 Eigenvalue-based stability analysis techniques ...................................................... 23
    3.2.2 Numerical computation of system’s state transition matrix .................................. 24
3.3 Conclusion ...................................................................................................................... 26

CHAPTER 4 ..................................................................................................................................28

PROPOSED SMALL-SIGNAL STABILITY ASSESSMENT METHOD .................................28

4.1 General concept and mathematics .................................................................................. 28

4.2 Practical considerations to accomplish requirements for the proposed method ............ 34

4.3 Additional considerations in order to enable real-time capability of the proposed technique ................................................................................................................................... 36

4.3.1 Chirp excitation signals ........................................................................................... 36

4.3.2 Parallel perturbations .............................................................................................. 37

CHAPTER 5 ..................................................................................................................................38

MODEL VALIDATION AND SAMPLE STABILITY ANALYSIS IN SIMULATION ..........38

5.1 Test system configuration .............................................................................................. 38

5.2 Proposed method results for PSCAD platform and in non-real-time ............................ 39

5.2.1 System with asymptotic stability ............................................................................ 39

5.2.2 System with marginal stability ................................................................................ 40

5.2.3 Small-signal stability analysis of the test bed by gradual decrement in load that cause instability ..................................................................................................................... 42

5.3 Proposed method results for GNC in PSCAD platform and non-real-time ................... 44

5.3.1 Results for asymptotic stable system and based on GNC ...................................... 44

5.3.2 Stability analysis of the test bed with marginal stability and through GNC ........... 45

5.3.3 GNC and small-signal stability investigation of unstable system ............................ 46

5.4 Developed test system in RSCAD and simulation results for the proposed technique in real-time .................................................................................................................................... 48

5.4.1 Test system configuration modifications in order to enable real-time capability 50

5.4.2 Instantiated test scenarios to study small-signal stability of the SST under different loading conditions and in real-time ....................................................................................... 52

CHAPTER 6 ..................................................................................................................................59

HARDWARE DEVELOPMENT AND EXPERIMENTAL IMPLEMENTATION ...............59

6.1 NLDL test bed ................................................................................................................ 60

6.1.1 Introduction to back-to-back/3-phase/2-level converters in the NLDL test bed .... 61
LIST OF FIGURES

Fig. 1. Linear approximation shows negative slope (impedance) for a CPL connected to PEC ......................................................... 8

Fig. 2. General feedback system schematic ....................................................................................................................................... 9

Fig. 3. Interconnected source-load representation of every PEDS .................................................................................................. 10

Fig. 4. Impedance measurement technique in the DC systems ........................................................................................................ 12

Fig. 5. Impedance measurement technique in the AC systems conducted in the \( d - q \) reference frame ........................................................................................................................................................................... 13

Fig. 6. Sample AC power system with the \( d-q \) impedances in the source-load interface .................................................. 16

Fig. 7. Ideal balanced injection with shunt current injection ........................................................................................................ 17

Fig. 8. Shunt injection circuit with inserting filtering impedances ............................................................................................... 17

Fig. 9. Series injection circuit with inserting filtering impedances ................................................................................................. 18

Fig. 10. Small-signal stability analysis algorithm based on source impedance/load admittance matrix realizations ................................................................................................................................. 20

Fig. 11. Algorithm and flowchart for the proposed small-signal stability analysis ........................................................................ 33

Fig. 12. Schematic of the 1st generation SST as a sample PEC with the source-load interface ...................................................... 38

Fig. 13. Time-domain results for the asymptotic stable SST connected to the RL load: (a) and (b) RMS values for the voltage and current of the secondary side; (c) and (d) active and reactive powers ........................................................................................................................................................................................................................................... 39

Fig. 14. Simulation results for the asymptotic stable SST connected to the RL load: (a) and (b) Actual values for the voltage and current of the secondary side in time-domain ........................................................................................................................................................................................................................................... 40

Fig. 15. Proposed stability metric showing the relative stability of the test bed for asymptotic stability ........................................................................................................................................................................................................................................... 40

Fig. 16. Time-domain results for the test system with the marginal stability: (a) and (b) Secondary side RMS voltage and current; (c) and (d) active and reactive powers ........................................................................................................................................................................................................................................... 41

Fig. 17. Simulation results for the marginal stable test bed: (a) and (b) Time-domain results for the voltage and current of the secondary side ........................................................................................................................................................................................................................................... 42

Fig. 18. Proposed stability criterion for the marginal stable test system ............................................................................................. 42

Fig. 19. Simulation results in time-domain for the unstable test system: (a) and (b) rms voltage and current in LV side of the SST; (c) and (d) active and reactive powers ........................................................................................................................................................................................................................................... 43
Fig. 20. Stability metric (unit circuit stability criterion) showing the test system becoming unstable

Fig. 21. Nyquist plot for the asymptotic stable test bed in s-plane

Fig. 22. Return-ratio contour for the marginal stable system in s-plane

Fig. 23. Test bed in the instable condition: (a) and (b) Time-domain results for the totally disordered voltage and current of the LV side

Fig. 24. Return-ratio plot in s-plane for unstable test system

Fig. 25. Unit circuit stability criterion (for the unstable case the value of return-ratio is greater than one)

Fig. 26. Simulator room with the RTDS racks in the CAPS

Fig. 27. IEEE-34 bus test system with integration of SSTs in distribution level

Fig. 28. Schematic of a SST used as a sample PEC with perturbations in source and load interfaces simultaneously (in order to enable real-time capability)

Fig. 29. Simulation results in RSCAD for (a) SST1 and (b) SST2 in their normal operation

Fig. 30. Real-time simulation results for the RSCAD test system under load shedding condition for (a) SST1 and (b) SST2

Fig. 31. Simulation results for the test system in RSCAD under (a) load increase condition for SST 1 and (b) load shedding condition for SST 2

Fig. 32. GNC for the SST 1 in RSCAD test system while its load increases

Fig. 33. Real-time simulation results for the RSCAD test system while (a) SST 1 sheds the load and (b) SST 2 increases the load

Fig. 34. GNC for the SST 2 in RSCAD test system under load increment condition for SST2

Fig. 35. PHIL schematic to study small-signal stability of the test system in real-time

Fig. 36. The NLDL test bed

Fig. 37. 3-phase boost rectifier

Fig. 38. 3-phase inverter (a) schematic (b) in the NLDL test bed

Fig. 39. Schematic of the NLDL test bed 3-level NPC converter (courtesy of NLDL test bed tutorial)
Fig. 60. PHIL experiment results (DC link voltage and load voltage and current) with 3 (kW) AC load and 2 (kW) DC load

Fig. 61. NHR 4600 (programmable 3-phase) AC load picture in the Energy Conversion and Integration Thrust Lab
LIST OF TABLES

Table 1: R and L values connected to the SSTs for the power decrement scenario ..................... 53

Table 2: Values for R and L connected to the SSTs while SST 1 power’s increases and SST 2 power’s decreases ......................................................................................................................... 54

Table 3: Values for R and L connected to the SSTs for load decrement in SST 1 and load increment in SST2......................................................................................................................... 56

Table 4: NHR 9200-4960 parameters ........................................................................................... 81
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
</tr>
<tr>
<td>AFE</td>
<td>Active Front End</td>
</tr>
<tr>
<td>APF</td>
<td>Active Power Filter</td>
</tr>
<tr>
<td>BTB</td>
<td>Back-to-Back</td>
</tr>
<tr>
<td>CPL</td>
<td>Constant Power Load</td>
</tr>
<tr>
<td>CHIL</td>
<td>Control Hardware-in-the-loop</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-Analog Converter</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>DGI</td>
<td>Distributed Grid Intelligence</td>
</tr>
<tr>
<td>DRER</td>
<td>Distributed Energy Storage Devices</td>
</tr>
<tr>
<td>DRER</td>
<td>Distributed Renewable Energy Resources</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FID</td>
<td>Fault Isolation Device</td>
</tr>
<tr>
<td>GEH</td>
<td>Green Energy Hub</td>
</tr>
<tr>
<td>GM</td>
<td>Gain Margin</td>
</tr>
<tr>
<td>GMPM</td>
<td>Gain Margin Phase margin</td>
</tr>
<tr>
<td>GNC</td>
<td>Generalized Nyquist Criterion</td>
</tr>
<tr>
<td>HIL</td>
<td>Hardware-in-the-Loop</td>
</tr>
<tr>
<td>IMU</td>
<td>Impedance Measurement Unit</td>
</tr>
<tr>
<td>KCL</td>
<td>Kirchhoff’s current law</td>
</tr>
<tr>
<td>KVL</td>
<td>Kirchhoff’s voltage law</td>
</tr>
<tr>
<td>LHP</td>
<td>Left Half Plane</td>
</tr>
<tr>
<td>LSSS</td>
<td>Large Scale System Simulation</td>
</tr>
<tr>
<td>NLAM</td>
<td>Non-linear Average-value Modeling</td>
</tr>
<tr>
<td>NLDL</td>
<td>Nonlinear dynamic loads</td>
</tr>
<tr>
<td>NPC</td>
<td>Neutral Point Clamped</td>
</tr>
<tr>
<td>ODE</td>
<td>Ordinary differential equation</td>
</tr>
<tr>
<td>PHIL</td>
<td>Power-Hardware-in-the-loop</td>
</tr>
<tr>
<td>PDE</td>
<td>Partial differential equation</td>
</tr>
<tr>
<td>PEC</td>
<td>Power Electronics-based Component</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>PEDS</td>
<td>Power Electronics-based Power Systems</td>
</tr>
<tr>
<td>PHIL</td>
<td>Power Hardware-in-the-Loop</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional-integral</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Lock Loop</td>
</tr>
<tr>
<td>PM</td>
<td>Phase Margin</td>
</tr>
<tr>
<td>PSCAD</td>
<td>Power System Computer Aided Design</td>
</tr>
<tr>
<td>RAS</td>
<td>Regions of Asymptotic Stability</td>
</tr>
<tr>
<td>RSCAD</td>
<td>Real time Simulator Computer Aided Design</td>
</tr>
<tr>
<td>RSC</td>
<td>Reliable and Secured Communications</td>
</tr>
<tr>
<td>RHP</td>
<td>Right Half Plane</td>
</tr>
<tr>
<td>RTDS</td>
<td>Real-time digital simulator</td>
</tr>
<tr>
<td>SST</td>
<td>Solid State Transformer</td>
</tr>
<tr>
<td>VSI</td>
<td>Voltage Source Inverter</td>
</tr>
</tbody>
</table>
ABSTRACT

Power Electronic-based Distribution Systems (PEDS) can provide excellent features such as load regulation, high power factor, and transient performance; especially in the large scale grids which are highly penetrated with the renewable energy resources, as well as innovative Power Electronic-based Components (PECs) such as Solid State Transformers (SSTs), Fault Isolation Devices (FIDs), machine drives, and inverters. Conversely, they are prone to exhibit negative impedance instabilities due to the regulated output voltage, high power factor and constant-power nature of the individual components in the system. Therefore, small-signal and large-signal stability assessments of the PEDS play a prominent role in the different stages of systems analyses such as preoperational (design), operational, and post-operational stages. Herein, various stability analysis techniques, along with their pros and cons, are described.

This work proposes to develop a novel “real-time” stability analysis criterion and technique to assess small-signal stability of the PECs in the contemporary distribution systems. This will consist of a new small-signal stability criterion as well as appropriate technique to assess small-signal stability of the PECs based on the proposed criterion. The proposed criterion is developed based on d-q impedance measurement technique and Nyquist criterion. The advantages of the proposed criterion and technique include the capability to be developed for real-time applications, the simplicity of development on software and hardware, and the use of a powerful algorithm to address small-signal stability of the PEDS, etc. The primary contribution of this work is the real-time stability analysis methodology; more specifically, the capability of the proposed criterion and technique to be implemented in a real-time platform. The parallel perturbation of source and load is one of the key features of the proposed method that enables real-time capability. In addition, the proposed stability criterion, based on impedance measurement and Nyquist stability criterion, contributes higher accuracy in small-signal stability assessments of the systems by providing a complete Nyquist contour of the system’s returnation matrix. Ultimately, this yields lighter computational loads, faster computation times, and more accurate evaluation of the system’s stability in a way that enables the assessment of the relative and absolute stability of the PEDS. Another advantage of the proposed technique is that it takes part of the system’s nonlinearities into account by perturbing the systems with chirp signal and in a range of frequencies, instead of exclusively fundamental frequency.
Hardware development and experimental implementation also is presented in this work. In the experimental implementation section of the proposed work, an Impedance Measurement Unit (IMU) is developed via Power Hardware-in-the-Loop (PHIL) experiment and measures source and load impedances in real-time. Subsequently, the proposed stability criterion is implemented on the real-time digital simulator (RTDS) and by utilizing information from the developed IMU, small-signal stability of the test bed is investigated in real-time.
CHAPTER 1

INTRODUCTION

1.1 Motivation and goal

Around the world, there has been a significant growth in utilizing PECs in power systems, due to the fact that they can considerably enhance power system characteristics such as power quality, voltage regulation, and power factor. Therefore, as the world braces for a sustainable energy future, large scale integration of variable power generation, as well as PECs into the grid, is on rise. However, PECs may have a significant effect on the stability of the large scale power systems, particularly, in a large scale power system that is congested due to the high PECs penetration. Therefore, compared to conventional power systems, the stability assessment of PEDS has considerably changed due to the capability of PECs to operate as negative impedances in the systems. In the small-signal viewpoint, Constant Power Loads (CPLs) can appear as negative impedance in the system, which intuitively has a destabilizing effect [1]. In other words, instability in PEDS is caused by the tendency of the power electronic-based components to behave as CPLs [2]. Therefore, the stability assessment of PEDS is a more critical task than in conventional power distribution systems, since therein small-signal stability should be addressed as well as steady-state and large-signal stabilities.

Several studies have been dedicated to PEC’s stability assessment to date. By looking deep into the literature, it is noticeable that so far the small-signal stability analysis methods have been addressed for design purposes of the PECs. In other words, they address the small-signal stability of the PECs in order to define permitted source/load impedances for the system to remain in a stable region. However, there has been no technique/criterion developed to assess the small-signal stability of the PECs in the operational stage to investigate the absolute and relative stability of a system while it is operating. This study describes a technique/criterion to address small-signal stability of the PECs in the operational stage. For this purpose, an impedance measurement-based technique is utilized to define the source impedance and load admittance. Subsequently, the small-signal stability of the system is investigated by Generalized Nyquist Criterion (GNC) utilizing obtained source/load impedances of the system. Furthermore, our developed technique makes it possible to assess the stability of the PECs in an operational stage.
Therefore, it is possible to extend (apply) this technique to real-time stability assessment applications.

1.2 State of the art

Stability studies for power systems may be categorized into three different stages with respect to the systems operating time: preoperational, operational, and post-operational stages. Conversely, from the system’s topology viewpoint, the stability of the systems may be divided into three types: steady-state, small-signal, and large-signal stability analyses [3]. Steady-state analysis is the initial step to approach a system stability study that provides significant understanding of the system behavior during normal operation. In the conventional power system stability studies, stability from a steady-state viewpoint is utilized [4]. In this research, aforementioned types of steady-state stability are not addressed and it is assumed that the system is stable in steady-state since it is a prerequisite condition for further analysis.

The small-signal analysis is the next step in a system stability study when the steady-state stability of the systems is provided. Small-signal stability is defined as in [5]: The capability to return to the identical stable operating point after the occurrence of a disturbance that leads to any changes in one or more of the state variables of a PEDS. If a disturbance in the power system causes a change in the state variables, the system is deviated from the equilibrium operating point. If afterward the system returns to its steady state, it is stable, whereas if the initial deviation from the steady state becomes ever larger, it is unstable.

Large-scale displacement, also known as transient or large-signal stability, is defined as [5]: “The capability of a power system to return to a stable operating point after the occurrence of a disturbance that changes its topology.” The tripping of a generator or a line, the sudden change of a load (including a load trip) which is equivalent to the change of a load to zero, and the occurrence of a fault are some cases in point. If one of the above disturbances occurs, the system is no longer in steady state. Different quantities in the system, such as rotor speeds and node voltages, start to change and to deviate from their steady state values. If the fluctuations of the system’s quantities damp out and the system settles at a stable operating point, it is considered stable. Conversely, when the deviation of the various quantities becomes greater, the system is unstable and will eventually collapse. The aforementioned definition of transient stability indicates that the electrical topology of the power systems will be change. This point is the main distinction between transient stability and small signal stability. An additional
difference between transient stability and small signal stability is that if a steady state is reached after a disturbance leading to a transient phenomenon, such as a change in the system’s topology, the new steady-state operating point can be different from the initial one. In contrast, if a system returns to a steady state after a gradual change in a state variable, the system remains at initial operating point, since there is not any change in the topology of the system [5].

In the small-signal analysis, stability of the systems will be investigated around a desirable operating point. Generally, a system might operate in various equilibrium points of interest. In this condition, in order to ensure overall stability of the system, small-signal stability has to be addressed at each equilibrium point. Small-signal stability techniques are mainly developed based on average linearized models around the equilibrium points which allow utilizing different analytical tools that can assist in the study, such as Nyquist, Bode, and Root locus plots. One common technique for small-signal stability assessment of the PEDS uses Middlebrook’s criterion [6] to ensure stability of the systems by encircling the Nyquist contour of $Z_{source}(s)/Z_{load}(s)$ in the unit circle in the s-plane. Small-signal stability assessments may be utilized for both design and operational purposes. There are several criteria and techniques that were developed based on Middlebrook’s criterion [6] in the associated research. Essentially, these methods are different in the degree of conservativeness in the design process of the PEDS.

Several methods for the purpose of control design were investigated in [7], [8], [9], [10], and [11]. By and large, these methods ensure the system’s stability by preventing encirclement of the (-1+j0) point by the Nyquist contour of $Z_s$ . $Y_l$. The first method is based on the Middlebrook criterion, which consists of a circle of radius $1/GM$ in the s-plane; where GM is Gain Margin (GM). For a given $Z_s$, this design criterion provides constraints for an allowable range of $Y_l$ as

$$|Y_l| < \frac{1}{|Z_s|GM}$$  \hspace{1cm} (1)

Obviously, with this constraint, the Nyquist plot of $Z_s$ . $Y_l$ is always within the circle. Therefore encirclements of the (-1+j0) point cannot occur, provided that GM is greater than 1. Due to an infinite Phase Margin (PM) demand, this method is likely to force artificially conservative designs. One alternative approach is the Opposing Component criterion [7] and [11]. In this method, the Nyquist diagram is required to fall to the right of a line at $s =1/GM$. Herein, the advantage over the Middlebrook criterion is that it can be less artificially conservative because it allows the Nyquist diagram to occupy a larger region of the s-plane.
There are also several other approaches which reduce the conservativeness of the design. The Gain Margin and Phase Margin (GMPM) criterion is a good case in point that considers PM in addition to GM and as a result decreases the degree of conservativeness [7]-[11].

Small-signal stability of the PECs does not always ensure the large-signal stability properties. Therefore, the large-signal stability analysis is essential for the PEDS since stability in all the operating points have to be addressed. Large-signal stability (which is also known as large-scale displacement stability [5]) is defined as: capability of a system to return to a stable operating point (it might be a new operating point) after a disturbance that changes the topology of the system. Since configurations of the system in the large-scale stability analysis are varied, typically it is achievable using computer simulations. It is inspected through the response of the system to various transient changes in the system and its capability to sustain or recover from disturbances [12]. Generally, considerable changes in the system parameters and/or states can cause transients in the system such as: load step, branch joining and/or disconnecting, fault occurrence, and in general any changes in the system’s structure are good cases which may cause transients in PEDS. By utilizing computer simulations, various operating points for the system may be defined. Subsequently, small-signal stability may be addressed in different operating points. Therefore, in order to ensure the overall stability of the systems, stability should be investigated from the large-signal as well as small-signal viewpoints.

One of the most well-known techniques associated with the small-signal stability analysis is the eigenvalue-based technique. This method has been used for the controller design to improve small-signal stability of the PECs in [13], [14], [15], and [16]; however, eigenvalue-based techniques are not practical for investigating the stability of the large scale power systems or PEDS. In [13] and [14], eigenvalues of the rectifier were calculated and small-signal stability was studied using two Lyapunov theories; the first states that stability of a linear model of a non-linear system ensures the stability of a corresponding non-linear system, and the second theorem states that if all the eigenvalues of a system are in the LHP, the system is stable. Conversely, in [16], new eigenvalue-based small-signal stability analysis of a multi-terminal dc network, along with its control design, was presented. Generally, in eigenvalue-based methods, small-signal state-space representations of the linearized model for the specific devices such as active rectifiers have to be found. Subsequently, based on state-space representation and the ABCD matrices, eigenvalues of the system are determined as a function of the system variables.
Therefore, it is possible to assist the stability analysis of the devices by eigenvalue analysis. The main problem for this method is that for every single PEC in the system, the small-signal state-space model has to be defined and overall stability of the system may not be investigated without dissociation of the system to the components. Furthermore, even dissociating the systems and providing the stability for each subsystem doesn’t necessarily guarantee the overall stability of the system. Therefore, aforementioned methods are proper methods for assessing stability of PECs include SST, active rectifier, and converter in the preoperational/design stages. Utilizing these techniques, stability of these systems might be studied in detail, as well as sensitivity analysis for the systems’ parameter. In this context, power system sensitivity analysis for small-signal stability assessment was addressed in [17] as well. This method is based on analytical and numerical approaches and investigates power system state-space matrix sensitivity with regard to system parameters. Subsequently, it identifies those parameters with greater impact on system eigenvalues, therefore, small-signal stability of the system.

Impedance measurement-based techniques are widely developed as well. For instance, in [18] and [19] impedance-based techniques were utilized to investigate stability of the proposed power systems. For this purpose, in [18] the system has to be perturbed at a variety of frequencies of interest and the associated responses are captured. Subsequently, linearized impedances at different frequencies/operating points are calculated. This method was well-developed and several research investigations have been accomplished by utilizing it. Hereinafter, the impedance measurement technique is described.

Bifurcation analysis based techniques have been utilized in [20] and [21] to address the stability of the power systems. In [20], stability of the standalone and parallel DC - DC converters were investigated utilizing nonlinear maps as well as state-space averaged model. In this paper, bifurcation analysis has been used to define the range of input voltages for a DC - DC converter in order to remain in the stable region. Furthermore, it has been shown that state-space averaged models cannot predict instability in some cases such as fast-scale dynamics, whereas, bifurcation analysis can predict it and capture the nonlinearities as well. Conversely, in [21] by utilizing bifurcation analysis, stability of the power systems including PECs were investigated. In this method, harmonics distortion, which was created by the switching of the PECs in the system, was taken into consideration. A periodic steady-state solution of the PEDS, which is the first step of stability assessment in this method, was efficiently computed through an iterative
Newton-Raphson method. This method has some restrictions. The most significant limitation from a power system viewpoint is that it is not applicable to the power electronics components with nonlinear loads and nonlinear control systems. Therefore, it is not practical for general PEDS.

Lyapunov techniques have been utilized for design purposes in large-scale stability assessment of specific types of PECs in [1], [2], [22], and [23], as well as small-signal in [13]. Since these methods addressed particular devices, they are not generic methods to be utilized for stability study of the PEDS. In [2], large-signal stability of the PEDS was investigated. In this regard, a new technique for estimating Regions of Asymptotic Stability (RAS) of the systems based on the Lyapunov stability theorem and genetic algorithm was developed. The RAS of an equilibrium state is the set of initial states which leads the system trajectories to the equilibrium state. In previous developed methods, the RAS was estimated based on sampling points in the region of the equilibrium state. Conversely, in the method proposed in [2], these sets are described by a quadratic Lyapunov function which is applicable to arbitrary Lyapunov functions as well. This feature reduces the complexity of computations in the procedure. Followed by finding the RAS estimation with Lyapunov function, optimizing the RAS function and solving the optimization problem with generic algorithm are well-developed via the aforementioned method.

### 1.3 Contribution

The small-signal stability assessment based on the impedance measurement technique and Nyquist criterion presented herein has two significant advantages over aforementioned techniques. The first advantage is the capability of this technique to be developed for real-time applications. Although real-time small-signal stability assessment of the PEDS is an extremely significant subject, it has not been addressed so far. By increment in penetration, of PECs in a large scale power grid, steady-state and large-signal stability analysis cannot ensure the overall stability of system. Small-signal stability of a system during operation has to be investigated as well to prevent instabilities in distribution and sub-transmission levels of the power systems. The second advantage of the proposed method is the simplicity of developing a powerful algorithm to address small-signal stability of the PEDS. In this method, several dominant concepts from previously developed stability techniques are utilized, and by taking advantage of the mathematics, the algorithm is modified to facilitate implementation.
CHAPTER 2

GENERAL REQUIREMENTS FOR SMALL-SIGNAL STABILITY ASSESSMENT

As aforementioned, in the introduction section, almost all the research developed for small-signal stability assessment of the PECs to date addressed stability of the systems based on Generalized Nyquist Criterion (GNC). These techniques were utilized to perform Nyquist stability evaluations in the power systems. This could be achieved by using an analogy of a transfer function obtained from a general feedback model and an input voltage transfer function of the interconnected source-load power system. In this section, GNC, along with Nyquist immittance (impedance and admittance) criterion was utilized for the interconnected source-load systems which are described. Furthermore, since small-signal impedance measurement is the common step for almost every stability assessment technique, different methods to measure small-signal impedance of the PECs in their AC and/or DC interfaces are interpreted as well. Subsequently, source impedance (or similarly load admittance) matrix realization is described in this section. In view of the fact that PEDS are nonlinear systems and majority of the developed techniques to address small-signal stability of these nonlinear systems address the linear representation of them, linearization of the obtained information for the source impedance/load admittance by utilizing matrix realization technique is also one of the significant prerequisites for the small-signal stability study techniques.

2.1 Negative impedance and dynamics of the PEDS under active loads

The improvement of power electronics technology leads to an increase in PEC penetration into the power generation, transmission, and distribution fields. These components introduce the opportunity to apply closed-loop control, which can significantly improve power, the quality of the delivered power, and also the control the power flow, in the PEDS as well as its consequences. Generally, PECs are nonlinear devices and subsequently their dynamics are coupled with the source(s)/load(s) connected to them. In order to have a regulated output in systems highly penetrated with the PECs, control strategies and controllers have to be applied to the systems, which in turn introduce new phenomena known as negative impedance and change the nature of stability study of the power systems.
Basically, power electronics-based converters with the regulated output voltage connected to constant power loads provide negative impedance characteristics at their input, since they consume constant power and work at a fixed current [24]. Considering an ideal example in which the power electronics-based converter is lossless, the input will also have a constant power characteristic, and as it is clearly shown in Fig. 1, the slope of the (i-v) curve, which is linearized impedance, would be negative. Although many large national grids can tolerate several PECs with the negative impedances, it is a critical issue for smaller power systems such as aircrafts, ships, hybrid-electric vehicles, and smaller islanded PEDS.

![Constant Power Load I-V Curve](image)

Fig. 1. Linear approximation shows negative slope (impedance) for a CPL connected to PEC

### 2.2 Generalized Nyquist Criterion

One of the most popular criteria for small-signal stability assessment of systems is GNC. Generally, in order to investigate stability of the systems, desirable system information (with respect to the chosen technique and/or method) has to be defined with one of the aforementioned techniques before the stability of the system can be accessed with generalized Nyquist and/or any other criterion.
In various literature sources, final stability evaluation of the systems has been done with diverse techniques and methods based on the Nyquist criterion. Generally in these methods, state equations are utilized to study stability of the systems. Essentially, the small-signal stability of the system can be analyzed by evaluating the eigenvalues of the Jacobean matrix of the system equations. In these methods, the system equations are linearized to obtain the state equations for a single operating point. Therefore, these equations, and as a result their corresponding eigenvalues, cannot represent all the characteristics of the systems. Consequently, these techniques by and large may be applied for operational stability studies.

Conversely, in a more advanced technique, the state equations and corresponding eigenvalues are obtained in different sets of operating conditions, which can be utilized to facilitate stability assessment of the systems in more general and adequate forms. Essentially, this method is known as a generalized Nyquist criterion and is commonly utilized in literature for preoperational (design) purposes [7]-[10]. Basically, this technique considers the range of source impedance to determine the range of load admittance of the system needed to maintain stability.

2.2.1 Generalized Nyquist evaluation

In the 1970s, MacFarlane and Postlethwaite extended the theory of Nyquist stability to a generalized Nyquist criterion which addresses matrix transfer functions. Essentially, the generalized Nyquist criterion could be used to characterize the stability of the systems under different loading conditions [18].

![Fig. 2. General feedback system schematic](image)

The output of the general model of the feedback system shown in Fig. 2 could be expressed as:

\[ y(s) = [I + G(s)K(s)]^{-1}G(s)u(s) \]  

(2)
Assuming all the modes of the open-loop systems are controllable and observable, this configuration will be closed-loop stable if and only if (IFF) the number of Right-Half Plane (RHP) zeros of the \(G(s)\) and \(K(s)\) is equal to the counter-clockwise encirclements around point (-1+0j) of the Nyquist contour of the open-loop transfer function:

\[
L(s) = G(s)K(s)
\]

(3)

Considering equation (3), the characteristic loci of return-ratio could be defined as the graphs of \(\lambda_t(s)\), which are the eigenvalues of \(L(s) = G(s)K(s)\). Subsequently, \(1 + \lambda_t(s)\) is the eigenvalue of the \(1 + L(s)\). Therefore, for every encirclement of the point (-1+j0) by the Nyquist contour, we will have an eigenvalue on the RHP. The proof of the duality for the eigenvalue theorem and generalized Nyquist theorem is treated in great detail in [18] by discussing the stability study results for a case study.

2.2.2 The Nyquist impedance-admittance (immittance) criterion

Generalized Nyquist evaluation was applied to the power system analysis as well as several other applications. The interconnected (source-load) PEDS is illustrated in Fig. 3. Using circuit analysis techniques, the terminal voltage \(v\) is determined by:

\[
v = \frac{v_{sT} - Z_s I_l}{1 + Z_s Y_I}
\]

(4)

This equation corresponds to the open-loop transfer function of the interconnected source-load system (Fig. 3) is stable, if \(1 + Z_s Y_I\) does not have any zeros in the closed RHP. By analogy and utilizing Nyquist theorem, the aforementioned system is stable, provided that the Nyquist evaluation of \(Z_s Y_I\) does not encircle -1 point [19].
From the Nyquist theorem and considering a transfer function with $1 + G(s)K(s)$ as its denominator, the number of unstable closed-loop poles for the system is equal to the number of unstable open-loop poles added to the number of clockwise encirclements of the point $(-1+j0)$ by the Nyquist evaluation of $G(s)K(s)$ on the Nyquist contour. By analogy, the number of unstable closed-loop poles in the aforementioned system, with $1 + Z_sY_l$ in the denominator, is equal to the number of unstable open-loop poles of $Z_sY_l$ (which in this case is zero, since herein the stand-alone source and load are stable) added to the number of clockwise encirclements of the Nyquist evaluation of $Z_sY_l$. Thus, for the abovementioned interconnected source-load system, the number of unstable closed-loop poles is equal to the number of clockwise encirclements of the point $-1+j0$ by the Nyquist contour of $Z_sY_l$. Therefore, a source-load system is stable IFF the Nyquist evaluation of $Z_sY_l$ does not encircle the point $(-1+j0)$ ([10] and [11]).

By using generalized impedance and admittance concepts, it is possible to utilize Nyquist immittance criterion for local and regional operating points of the system; whereas the impedance $Z_s(s)$ (or admittance $Y_l(s)$) is a unique complex number at a given frequency.

### 2.3 Small-signal impedance measurement techniques

One of the most significant and well-developed techniques for small-signal stability analysis is the impedance measurement technique. This technique was widely used for stability studies for both DC and AC interfaces of PEDS in previous research. Taking DC and AC converters into consideration, small-signal stability analysis may be categorized into DC and AC systems, respectively. For most integrated power systems, stability can be affected at both the DC and AC links. There are various choices of how to achieve stability at the AC and/or DC links, ranging from passive to active techniques. Basically in a DC stability study, stability of the hybrid AC/DC system will be investigated in the DC interface; whereas in an AC stability study of the same system, the stability criterion will be analyzed from the AC interface.

Since in this technique it is desirable to eventually find a range of source impedance and/or load admittance in order to maintain in a stable region for a specific PEDS, it is more appropriate to consider it as a preoperational technique in most cases. Several methods were previously developed based on impedance measurement techniques. Herein a method based on perturb-and-observe algorithm for impedance measurement is discussed. Since this method needs a sophisticated and complex process, in different studies impedance measurement is
separated into different categories, such as DC and AC impedance measurement, to make the
stability assessment procedure as efficient as possible.

2.3.1 Impedance measurement at DC interface of a PEC

Impedance measurement at the DC interfaces is known as the first step in DC stability
studies in literature. This method is straightforward and quite simple to employ, compared to the
AC stability analysis methods. In order to investigate stability of the system through DC stability
studies, it is only necessary to capture one set of date from the system and a d-q transform is not
required; whereas, AC stability study is slightly more sophisticated and it is quite easy to
measure the impedance in DC systems. Generally, the system’s voltage and current has to be
perturbed and then by measuring the system’s response at the source-load interface, the DC
source and load impedance may be calculated. The impedances could then be calculated from
(5). Fig. 4 illustrates the DC system and source-load interface, and the location of the
perturbation signals in the system [25].

\[ Z_S(s) = \frac{V(s)}{I_S(s)} \]
\[ Z_L(s) = \frac{V(s)}{I_L(s)} \]

(5)

![Fig. 4. Impedance measurement technique in the DC systems](image)

2.3.2 Impedance measurement at AC interface of a PEC

Generally, AC systems stability analysis is conducted in the \( d - q \) reference frame since
this is the sole way to deal with constant values at synchronous frequency. The main advantage
of this transformation is that there will be two components to consider for analysis in the balanced three-phase systems (since zero components are zero). The basic algorithm for such systems is similar to what is used for DC systems. The only distinction being that for AC systems two independent perturbations ($i_{pq}$ and $i_{pd}$) are required (since we are dealing with $d$ and $q$ subsystems); whereas in DC systems single perturbation is sufficient [25]. Fig. 5 depicts an AC system which is considered in the $d – q$ reference frame.

After perturbations are made, the responses have to be measured at the interface and the impedance can be calculated by:

$$\begin{align*}
\begin{bmatrix}
\tilde{v}_{d1}(s) \\
\tilde{v}_{q1}(s)
\end{bmatrix} &= Z_{Sdq}(s) \begin{bmatrix}
\tilde{i}_{d1}(s) \\
\tilde{i}_{q1}(s)
\end{bmatrix} \\

\begin{bmatrix}
\tilde{v}_{d1}(s) \\
\tilde{v}_{q1}(s)
\end{bmatrix} &= Z_{Ldq}(s) \begin{bmatrix}
\tilde{i}_{d1}(s) \\
\tilde{i}_{q1}(s)
\end{bmatrix}
\end{align*}$$

(6)

In (6) $\tilde{i}_{d1}$ and $\tilde{i}_{q1}$ are the system’s current responses in the source-side to the first perturbation and in the $d$ and $q$ accesses respectively; whereas $\tilde{i}_{d1}$ and $\tilde{i}_{q1}$ are the system’s
current responses in the load-side to the first perturbation and in the \( d \) and \( q \) accesses respectively. In addition, \( \tilde{v}_{d1}(s) \) and \( \tilde{v}_{q1}(s) \) are the system’s voltages according to the first perturbation and in the \( d \) and \( q \) reference frames. The second perturbation is made afterwards and by setting \( i_{pq} \) to zero and injecting \( i_{pd} \) current. For a second time the responses in the source and load interfaces are captured/measured to obtain (7):

\[
\begin{bmatrix}
\tilde{v}_{d2}(s) \\
\tilde{v}_{q2}(s)
\end{bmatrix}
= Z_{Sdq}(s)
\begin{bmatrix}
\tilde{i}_{Sd2}(s) \\
\tilde{i}_{Sq2}(s)
\end{bmatrix}
\]

(7)

\[
\begin{bmatrix}
\tilde{v}_{d2}(s) \\
\tilde{v}_{q2}(s)
\end{bmatrix}
= Z_{Ldq}(s)
\begin{bmatrix}
\tilde{i}_{Ld2}(s) \\
\tilde{i}_{Lq2}(s)
\end{bmatrix}
\]

The symbols in (7) represent similar components to (6), the only difference is that herein these are the responses to the second perturbations.

By combining (6) and (7) it is possible to get:

\[
\begin{bmatrix}
\tilde{v}_{d1}(s)\tilde{v}_{d2}(s) \\
\tilde{v}_{q1}(s)\tilde{v}_{q2}(s)
\end{bmatrix}
= Z_{Sdq}(s)
\begin{bmatrix}
\tilde{i}_{Sd1}(s)\tilde{i}_{Sd2}(s) \\
\tilde{i}_{Sq1}(s)\tilde{i}_{Sq2}(s)
\end{bmatrix}
\]

(8)

\[
\begin{bmatrix}
\tilde{v}_{d1}(s)\tilde{v}_{d2}(s) \\
\tilde{v}_{q1}(s)\tilde{v}_{q2}(s)
\end{bmatrix}
= Z_{Ldq}(s)
\begin{bmatrix}
\tilde{i}_{Ld1}(s)\tilde{i}_{Ld2}(s) \\
\tilde{i}_{Lq1}(s)\tilde{i}_{Lq2}(s)
\end{bmatrix}
\]

Whereas \( Z_{Sdq}(s) \) is the source impedance matrix and \( Z_{Ldq}(s) \) is the load impedance matrix and is equal to \( I/Y_{Ldq}(s) \) (has a reverse relationship to the load admittance matrix). In addition, impedance matrices can be solved from (8):

\[
Z_{Sdq}(s) = \begin{bmatrix}
\tilde{v}_{d1}(s)\tilde{v}_{d2}(s) \\
\tilde{v}_{q1}(s)\tilde{v}_{q2}(s)
\end{bmatrix}
\begin{bmatrix}
\tilde{i}_{Sd1}(s)\tilde{i}_{Sd2}(s) \\
\tilde{i}_{Sq1}(s)\tilde{i}_{Sq2}(s)
\end{bmatrix}^{-1}
\]

(9)

\[
Z_{Ldq}(s) = \frac{I}{Y_{Ldq}(s)} = \begin{bmatrix}
\tilde{v}_{d1}(s)\tilde{v}_{d2}(s) \\
\tilde{v}_{q1}(s)\tilde{v}_{q2}(s)
\end{bmatrix}
\begin{bmatrix}
\tilde{i}_{Ld1}(s)\tilde{i}_{Ld2}(s) \\
\tilde{i}_{Lq1}(s)\tilde{i}_{Lq2}(s)
\end{bmatrix}^{-1}
\]

In this dissertation a method for impedance measurement technique based on perturb-and-observe algorithm is discussed. In this technique, the system is perturbed by series voltage
injection and/or shunt current injection and the system’s response is measured in the source and load interfaces. Subsequently, by utilizing (6) - (9) it is possible to calculate source/load impedances in \( d - q \) coordinates.

### 2.3.3 Impedance measurement for high power factor rectifiers

Impedance measurement methods for high power factor rectifiers use a simpler modified version of the algorithm used for AC impedance measurement techniques. Basically, stability at the AC interfaces which feed high power factor rectifiers could be assessed by employing a Generalized Nyquist Criterion to the loop-gain or return-ratio matrix \( L_{dq}(s) \) [29]. In general, \( L_{dq}(s) \) can be calculated as:

\[
L_{dq}(s) = Z_{dq} Y_{Ldq} = \begin{bmatrix}
Z_{Sdd}(s) & Z_{Sdq}(s) \\
Z_{Sqd}(s) & Z_{Sqq}(s)
\end{bmatrix}
\begin{bmatrix}
Y_{Ldd}(s) & Y_{Ldq}(s) \\
Y_{Lqd}(s) & Y_{Lqq}(s)
\end{bmatrix}
\]

In this study, a standard high power factor multi-pulse rectifier is utilized and studied as a representative PEC, and afterward, the results of this study are extended to apply to every high power factor PECs. Standard AC interfaces of a three-phase power system feeding a high power factor multi-pulse rectifier are depicted in Fig. 6. In [29], it was proven that “all constant power load dynamics are reflected on the \( d - d \) channel”. Therefore, for high power factor rectifiers, it is acceptable to neglect all the other channels of input admittance \( Y_{Ldq} \) in the return-ratio matrix calculation. Consequently, the equation (10) is derived as:

\[
L_{dq}(s) \approx \begin{bmatrix}
Z_{Sdd}(s) & Z_{Sdq}(s) \\
Z_{Sqd}(s) & Z_{Sqq}(s)
\end{bmatrix}
\begin{bmatrix}
Y_{Ldd}(s) & 0 \\
0 & 0
\end{bmatrix}
\approx \begin{bmatrix}
Z_{Sdd}(s)Y_{Ldd}(s) & 0 \\
Z_{Sqd}(s)Y_{Ldq}(s) & 0
\end{bmatrix}
\approx \begin{bmatrix}
l_1(s) & 0 \\
l_2(s) & 0
\end{bmatrix}
\]

Also it was proven in [6] that, in this condition, the small-signal stability at the input terminals of the multi-pulse rectifier is determined by the characteristic loci described by the eigenvalues of the corresponding return-ratio matrix \( L_{dq}(s) \). Given the input dynamics of the rectifier, the eigenvalues of \( L_{dq}(s) \) at the AC interface are given by (11). Consequently, only the eigenvalue associated to the \( d - d \) channel (i.e., \( l_1(s) = Z_{Sdd}(s).Y_{Ldd}(s) \)) can actually encircle the critical point \((-1 + j0)\), and thus be the cause of instability. The remaining eigenvalue \( l_2(s) = \ldots\)
$Z_{sd}(s), Y_{ld}(s)$, associated to the $q - d$ channel, was shown to remain stationary at the origin of the complex plane and therefore be incapable of causing instabilities [29].

![Sample AC power system with the d-q impedances in the source-load interface](image)

**Fig. 6.** Sample AC power system with the $d$-$q$ impedances in the source-load interface

### 2.4 Ideally balanced injection in impedance measurement techniques

As previously mentioned, perturbing a system is one of the most significant and common steps of impedance measurement techniques. Generally, perturbing the systems can be accomplished either by current or voltage source, allowing for the use of two different techniques: shunt current injection and series voltage injection. It is also possible to utilize impedance filters instead of power sources to perturb the systems. Even though the system bus needs to be broken into two parts to insert the injection device, the series voltage injection is more efficient in changing the perturbation distribution than inserting filtering impedance.

In a stiff system, regardless of the shunt injection and series injection, perturbation power is likely to flow into just one side of the system; however it is important that perturbations flow into both of them to achieve a good measurement. Therefore, in the shunt current injection with the current source, for three-phase systems, a three-phase current source with power of about 1% to 10% of the main power source is connected in parallel between source and load. This is shown in Fig. 7.
As aforementioned, inserting filtering impedance technique can be used for the shunt current injection. In this situation, the VSI is connected to the system via an output filter. This filter attenuates the switching frequency ripple and the converter operates with current control. Furthermore, there is no active power required since the measurement frequency does not include DC (except for compensating the loss of the converter). Therefore, the VSI in the system is designed to run without a DC side power supply, which is similar to an Active Power Filter (APF), and a DC voltage loop is applied to the circuit for this means. In order to avoid interference on the injection, the bandwidth of the DC control loop is designed to be lower than the lowest measurement frequency \[30\]. Fig. 8 illustrates shunt injection circuit with the inserted impedance filters:

As aforementioned, inserting filtering impedance technique can be used for the shunt current injection. In this situation, the VSI is connected to the system via an output filter. This filter attenuates the switching frequency ripple and the converter operates with current control. Furthermore, there is no active power required since the measurement frequency does not include DC (except for compensating the loss of the converter). Therefore, the VSI in the system is designed to run without a DC side power supply, which is similar to an Active Power Filter (APF), and a DC voltage loop is applied to the circuit for this means. In order to avoid interference on the injection, the bandwidth of the DC control loop is designed to be lower than the lowest measurement frequency \[30\]. Fig. 8 illustrates shunt injection circuit with the inserted impedance filters:

Fig. 7. Ideal balanced injection with shunt current injection

Fig. 8. Shunt injection circuit with inserting filtering impedances
Conversely, for series injection applications with the inserted filtering impedance technique, the VSI is initially connected to an output filter and then connected to the system with a transformer. In this condition, the transformer boosts the current capability of the injection circuit to assist in carrying full system currents, as well as providing the isolation [30]. The series injection circuit with inserting filtering impedances is shown in Fig. 9.

**Fig. 9. Series injection circuit with inserting filtering impedances**

### 2.5 Source impedance/load admittance matrix realizations

One of the most significant prerequisites for impedance measurement-based techniques is source and load impedance/admittance realization. In order to investigate the small-signal stability of a system through impedance measurement techniques, as was described previously, a proper impedance matrix has to be initially defined. There are several methods that have developed different algorithms for defining impedance matrices. The following part of the study describes, presents, and utilizes one of the most adequate and simplest algorithms for obtaining impedance matrices based on algorithms developed in [18]. Non-Linear Average Model (NLAM) of the PECs, obtained from a detailed switching model of the system could be represented in a nonlinear state form as:

\[
\begin{align*}
\frac{dX}{dt} &= f(X(t), S(t), u(t)) \\
Y &= g(X(t), S(t), u(t))
\end{align*}
\]  

(12)
Where \( S(t) \) represents the two states of a switch in the converters. The state vector, \( X(t) \), may include the voltage across the capacitors, the currents in the inductors, and the states associated with the PI controllers of the converters [18]. The input vector \( u(t) \) may include the fixed field voltage (or speed) of the generator and/or motor, and the voltage control references for the converters. Averaging the system variables of equation (12), yields:

\[
\frac{d\bar{X}}{dt} = f(\bar{X}(t), \bar{S}(t), \bar{u}(t))
\]

\[
\bar{y} = g(\bar{X}(t), \bar{S}(t), \bar{u}(t))
\]

(13)

Where \( \bar{u}(t) \) is the continuous function representing the average of the variable \( u(t) \). It is important to note that, in general, averaging of the switching functions is possible only for systems where switching ripple is small. The averaging techniques yield NLAMs which are differentiable and therefore the model can be linearized either by numerical methods (for sophisticated models) or analytically (for simpler models).

In order to obtain a transfer function, which is needed for generalized Nyquist criterion, the system must be divided into source and load subsystems. Subsequently, transfer functions of \( Z_s \) and \( Y_l \) must be computed from NLAM. The state form of the equation (12) may be linearized around an operating point as:

\[
\frac{dX}{dt} \cong AX + Bu
\]

\[
y \cong CX + Du
\]

(14)

Where \( ABCD \) are the Jacobian matrixes of \( f \) and \( g \) with respect to \( x \) and \( u \). Therefore, the transfer function matrix \( T \) with inputs \( u \) and outputs \( y \) could be described as:

\[
T = C[sI - A]^{-1}B + D
\]

(15)

Any configuration of states and inputs may be used to generate a transfer function from the nonlinear state-space model. If states are specified as an input, they must be set to a constant nominal value, which is determined as the operating point. For instance, regarding \( Z_{dqs} \), the inputs should be currents and the outputs should be voltages.

Generally, in order to obtain \( Z_{dqs} \) or \( Y_{dql} \) (source impedance/load admittance) ABCD realization matrices have to be defined first. Subsequently, transfer matrices need to be calculated as a function of frequency. Afterwards, the eigenvalues of the \( Z_{dqs}, Y_{dql} \) at each frequency should be determined. Fig. 10 illustrates a detailed flowchart of the different steps to
investigate small-signal stability of the system, as well as transfer function determination required for the generalized Nyquist test [14].

Fig. 10. Small-signal stability analysis algorithm based on source impedance/load admittance matrix realizations
CHAPTER 3
DIFFERENT SMALL-SIGNAL STABILITY ANALYSIS TECHNIQUES

The nature of PEDS (three-phase AC distribution systems) is changed by introducing and increasing the penetration of the PECs such as power electronics-based converter, motor drives, and Distributed Renewable Energy Resources (DRER) into the systems. These devices are mostly used to provide power to loads and filtering functions as well as to convert between forms of electrical energy. Three-phase inverters, three-phase rectifiers, motor drives, AC-AC converters, and three-phase active filters are good cases in point. Basically, increasing the number of PECs in the PEDS can possibly threat the stability of the system from small-signal point of view, due to introducing negative impedance into the system. To date, several methods/techniques were dedicated to the small-signal stability of PEDS high penetrated with the PECs. In this section some of these methods are categorized by their basic concepts and discussed. Furthermore, negative impedance characteristics of the PECs (which caused by CPLs/active loads) are described.

3.1 Generalized immittance-based techniques

As aforementioned, PEDS exhibit nonlinear dynamics during operating in various conditions. Therefore, the linear models of the systems vary in different conditions and operating points. The analogy of the general feedback model and interconnected source-load system was discussed in 2.2.2. Furthermore, the Nyquist immittance criterion was described. This part describes some of the methods developed based on this criterion. Basically, load impedance/load admittance (immittance) characteristics of the systems have to be defined and addressed in all the developed methods based on Nyquist immittance criterion. Therefore, finding immittance characteristics of the system is a common part for these methods. After finding immittance for a system, small-signal stability can be studied with different criteria such as Middlebrook [6], unit circle [38], and GMPM [7] criteria.

In order to obtain load and/or source constraint in design process of PEDS, Middlebrook first stated a criterion that stability of a system can be ensured if the Nyquist contour of product of the source impedance and load admittance remains within a unit circle [6]. This criterion was described by (1). The main problem for Middlebrook criterion is the high degree of conservativeness in the assessments. Afterward, a new criterion for small-signal stability analysis
of PEDS in their DC links was proposed in [7]-[10] and [31] which diminished artificial conservativeness in stability assessment procedure. The generalized immittance-based method was used to develop a load admittance constraint based on generalized source impedance and vise-versa.

By and large, all the design techniques are applied to a known system at an operating point. In other words, these techniques have focused on local dynamic stability. However, PEDS normally operate through the full range of operating conditions and it is desirable to study the stability of the systems in a single analysis. By utilizing the concept of generalized immittance, the regional dynamic stability can be studied in an almost identical way to the problem of local dynamic stability [7]-[10]. This technique is developed based on the Nyquist criterion and it is counted as a design technique which can be utilized to define stable region of the device as well.

Basically, in generalized immittance based method, nonlinearities of the PEDS were considered by the concept of generalized impedance and generalized admittance sets. By taking into account every possible model, small-signal stability of the system can be guaranteed for all operating points. Likewise, the use of generalized impedance and admittance sets can be used to take uncertainties, variations in parameters, and operating conditions into consideration. Some considerations of this method are:

1. Non-Linear Average-Value Model (NLAM) of the systems is applicable.
2. Small-signal linear model of the system should be obtained from NLAM by either analytical or numerical methods at different operating points.
3. Linearized models should only be obtained after steady-state is reached and that for obtaining generalized immittance from it. Basically, representation of the model should be linearized over a range of operating points.

In order to obtain a generalized plant, initially the system has to be linearized in every operating point of interest. Afterward, state-space descriptions must be defined and subsequently generalized impedance can be obtained from state-space description.

Generalized immittance-based stability technique are widely used to date and based on the stability criterion the forms of the immittance characteristics are different. For instance, for a DC system this could be a one-dimensional matrix whereas for an AC system transferred to the synchronous (d-q) reference frame it is a [2 by 2] matrix. Equations (5) and (9) represent immittance matrices for DC and AC systems respectively.
3.2 **Numerical and computational-based techniques**

In addition to the stability methods based on immittance characteristics, there are some methods developed based on numerical and computational techniques to define state-space matrix/transfer function/ Lyapunov function. In order to address the small-signal stability of the systems by utilizing aforementioned techniques, the system has to be linearized around operating points and state equations of the linearized model has to be obtained. In other words, in order to investigate small-signal stability of PEDS with the Nyquist criterion, obtaining transfer function and/or state-space representation of the systems are essential. In this section, the numerical and computational based techniques to realize a transfer function, and/or state-space representation, from a small-signal linear model of the NLAM are discussed.

3.2.1 **Eigenvalue-based stability analysis techniques**

Eigenvalue-based Methods have been used for the design of controller to improve small-signal stability of the PECs in [13], [14], [15] and [16]. In [13] and [14] eigenvalues of the rectifier were calculated and small-signal stability was studied using two Lyapunov theories; which first states that stability of a linear model of non-linear system, ensures the stability of a corresponding non-linear system and the second theorem states that if all the eigenvalues of a system are in the LHP, the system is stable. Conversely, in [16] new eigenvalue based small-signal stability analysis and control design of a multi-terminal DC network was presented. In this work, a test network was developed with a combination of conventional synchronous, offshore wind generators, and Voltage Source Converters (VSC). Subsequently, small-signal stability analysis of the test bed was assessed under small and large perturbations through eigenvalue analysis. Generally, in eigenvalue based methods, small-signal state-space representation of the linearized model for the specific devices such as active rectifiers were found. Subsequently, based on state-space representation and the ABCD matrices, eigenvalues of the system were determined as a function of the system variables. Therefore, it assists stability analysis of the devices in a simple way. The main problem for this method is that for each PEC in the system the small-signal state-space model has to be defined and overall stability of the system may not be investigated without dissociation of the system to the components. Furthermore, even with the dissociation of the systems and providing the stability for each subsystem, the overall stability of the system is not necessarily guaranteed. Therefore, aforementioned methods are proper to be
utilized for the stability assessment of the PECs such as, SST, active rectifier, and converter in the preoperational/ design stages. Utilizing these techniques stability of these systems might be studied in detail as well as sensitivity analysis for the systems’ parameter. In this context, power system sensitivity analysis for small-signal stability assessment was addressed in [17] as well. This method is based on analytical and numerical approaches and investigates power system state-space matrix sensitivity with regard to system parameters. Subsequently, it identifies those parameters with greater impact on system eigenvalues, therefore, small-signal stability of the system.

3.2.2 Numerical computation of system’s state transition matrix

This small-signal stability assessment method has been developed based on computation of the transmission matrix over a cycle of the fundamental frequency time interval in [32], [33], [34], [35], and [36]. This method is appropriate for NLAMs and switching models of the any PEDS with and without nonlinear elements.

Generally, any form of power system can be described by a set of integro-differential algebraic equations in the form of:

\[
\begin{bmatrix}
e(t) \\
0
\end{bmatrix} = \begin{bmatrix}
g_1\left(\frac{dx(t)}{dt}, \frac{dy(t)}{dt}, x(t), y(t), u_o(t)\right) \\
g_2\left(\frac{dx(t)}{dt}, \frac{dy(t)}{dt}, x(t), y(t), u_o(t)\right)
\end{bmatrix}
\] (16)

Where, \(e(t)\) is the vector for external excitation, \(x(t)\) is the vector of observable states, \(y(t)\) is the vector of internal state variables, and \(u_o(t)\) is the vector of independent (open-loop) controls.

In order to realize the transition matrix of the dynamical systems, it is possible and more convenient to construct it from modified form of (16). These equations can be derived as a general form of:

\[
\begin{bmatrix}
i(t) \\
0
\end{bmatrix} = \begin{bmatrix}
f_1(v(t), y(t), v(t), y(t), u(t)) \\
f_2(v(t), y(t), v(t), y(t), u(t))
\end{bmatrix}
\] (17)

Where, \(i(t)\) is the current vector, \(v(t)\) is the voltage vector across the variables-states, \(y(t)\) is the internal state variables, and \(u(t)\) is the vector of independent controls. The aforementioned equation can be linearized. Consequently, the linear differential equations are in the general form:
\[
\begin{bmatrix}
i(t) \\
y(t)
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
v(t) \\
y(t)
\end{bmatrix} +
\begin{bmatrix}
B_{11} & B_{12} \\
B_{21} & B_{22}
\end{bmatrix}
dt
\begin{bmatrix}
v(t) \\
y(t)
\end{bmatrix}
\]  
(18)

Utilizing a suitable numerical method, integration of the above equations with a time step of \(h\) for the system will result:

\[
\begin{bmatrix}
i(t) \\
y(t)
\end{bmatrix} =
\begin{bmatrix}
Y_{11} & Y_{12} \\
Y_{21} & Y_{22}
\end{bmatrix}
\begin{bmatrix}
v(t) \\
y(t)
\end{bmatrix} -
\begin{bmatrix}
P_{11} & P_{12} \\
P_{21} & P_{22}
\end{bmatrix}
\begin{bmatrix}
v(t-h) \\
y(t-h)
\end{bmatrix} -
\begin{bmatrix}
C_{11} & C_{12} \\
C_{21} & C_{22}
\end{bmatrix}
\begin{bmatrix}
i(t-h) \\
0
\end{bmatrix}
\]  
(19)

Considering Kirchhoff’s current law (KCL) for each node of the system, nodal representation of the (19) for each node is:

\[
\begin{bmatrix}
0 \\
0
\end{bmatrix} =
\begin{bmatrix}
Y_{s11} & Y_{s12} \\
Y_{s21} & Y_{s22}
\end{bmatrix}
\begin{bmatrix}
v(t) \\
y(t)
\end{bmatrix} -
\begin{bmatrix}
P_{s11} & P_{s12} \\
P_{s21} & P_{s22}
\end{bmatrix}
\begin{bmatrix}
v(t-h) \\
y(t-h)
\end{bmatrix} -
\begin{bmatrix}
C_{s11} & C_{s12} \\
C_{s21} & C_{s22}
\end{bmatrix}
\begin{bmatrix}
i(t-h) \\
0
\end{bmatrix}
\]  
(20)

The state transition equations for the system can be defined using (20) by following equation set:

\[
\begin{bmatrix}
v(t) \\
y(t)
\end{bmatrix} =
\begin{bmatrix}
Y_{s11} & Y_{s12} \\
Y_{s21} & Y_{s22}
\end{bmatrix}^{-1}
\begin{bmatrix}
P_{s11} & P_{s12} \\
P_{s21} & P_{s22}
\end{bmatrix}
\begin{bmatrix}
v(t-h) \\
y(t-h)
\end{bmatrix} +
\begin{bmatrix}
Y_{s11} & Y_{s12} \\
Y_{s21} & Y_{s22}
\end{bmatrix}^{-1}
\begin{bmatrix}
Q_1(t-h) \\
Q_2(t-h)
\end{bmatrix}
\]  
(21)

Finally, using the state transition equation, small-signal stability analysis of the system can be conducted by eigenvalue analysis of the state transition matrix which was found by the numerical method in the previous step. Our ultimate goal herein is to define eigenvalues of the PEDS in order to address stability. There is a theoretical relationship between eigenvalues of the state transition matrix and the eigenvalues of the systems which assists analyzing the overall system’s small-signal stability by utilizing eigenvalues of the state transition matrix. This relationship simply can be denoted as:

\[
\lambda_c = \alpha + j \beta \\
\lambda_d = e^{\lambda_c T} = e^{\alpha T} e^{j \beta T} = r e^{j \theta} \\
\therefore r = e^{\alpha T}
\]  
(22)

Where, \(\lambda_c\) represents the eigenvalues of the state-space matrix and \(\lambda_d\) illustrates the eigenvalues of the transition matrix. Based on the Nyquist criterion, the PEDS will be stable IFF the real part of the eigenvalues are negative. Equation (22) depicts that if \(\alpha\) is negative, then \(r\) will be less than 1.0. Consequently, in order to have a small-signal stable system the eigenvalues of the system should be at the LHP; which will result the eigenvalues of the state transition matrix to be within a unit circuit centered at the origin.
The small-signal stability of the PEDS can be described with the eigenvalues of the state transition matrix by utilizing the aforementioned theory. The eigenvalues of the state transition matrix may be plotted on the complex plane and if all of them are encircled by a unit circuit, centered at the origin, the small-signal stability of the PEDS is provided. Furthermore, the distance between eigenvalues and the boundary of the unit circuit reveals the degree of stability. In other words, as eigenvalues of the transition matrix get closer to the border of the unit circle, it is more likely to have an unstable system.

### 3.3 Conclusion

In addition to the stability methods based on immittance characteristics, some studies are allocated to small-signal stability analysis using numerical and computational methods. These methods are also called “model analysis-based methods” and may be utilized different numerical and computational techniques to address small-signal stability of the systems with analyzing their models. Model analysis-based methods are essentially divided into different two main categories of eigenvalue-based methods and the methods for defining a system’s state transition matrix by numerical computation. Eigenvalue-based technique mainly has been used for the design of controller to improve small-signal stability of the PECs [14], [15], [16], and [17]. However, eigenvalue-based techniques, and more generally model analysis-based methods, are not the best solutions for investigating the stability of the large scale systems.

Basically model analysis-based methods separate systems into parts and pieces and define state-space equations, or optionally Transfer Functions (TFs) or state transition matrices, for each part of the systems. By achieving state-space equations (or TFs or state transition matrices) of each part and also finding the relationship between each part and overall system, it is possible to define overall state-space equation (or TF or state transition matrix) of the system. Subsequently eigenvalues of the systems may be calculated by using state-space equation and having all the eigenvalues in the LHP, the system is stable. In other words, in order to address the small-signal stability of the systems by utilizing aforementioned techniques, the system has to be linearized around operating points and state space equation (or TF or state transition matrix) of the linearized model has to be obtained.

One of the most prominent advantages of these techniques is that the stability study obtained from these techniques is able to define the range of the source/load impedances of the
system in order to operate in a stable region. Therefore, these methods are widely utilized for stability analysis of the PECs in the design stage. Conversely, compared to the proposed method in this paper, these methods have some disadvantages as follows:

- Since the system should be linearized around different operating points, single computation/calculation is required for stability study in each operating point, and thus multiple computations are required to define system’s global stability solution. This means model analysis-based methods are computationally complex and require a long computation/calculation time, and as a result they are not capable of assessing small-signal stability of the systems in real-time.

- Even small changes in the overall distribution system will result into the new/different state space equation (or TF or state transition matrix) for the overall system either by changing in the state space equation (or TF or state transition matrix) of one or several subsystems or by changing the system’s configurations that results to the new relationship between overall system and its subsystems.
CHAPTER 4

PROPOSED SMALL-SIGNAL STABILITY ASSESSMENT METHOD

4.1 General concept and mathematics

In this study, a novel stability assessment technique is proposed which essentially investigates the small-signal stability of the PECs while they are operating. This technique is based on the AC $d-q$ impedance measurement theory, in the operational stage as opposed to design stage, and utilizes GNC to assess the stability of the systems; the difference being that the injected perturbations are in a range of frequencies instead of solely the system’s fundamental frequency. By using generalized impedance and admittance concepts (perturbing the system in a range of frequencies), it is possible to utilize Nyquist immittance criterion for local and regional operating points of the system; whereas the impedance, $Z_s(s)$, or admittance, $Y_l(s)$, is a unique complex number at any given frequency. Herein, since it is desirable to monitor a system’s stability while it is operating and at any given time, the system has to be perturbed persistently, and by utilizing the system’s response to the perturbations, $Z_{sdq}$ and $Y_{ldq}$ could be calculated in the time-domain. After this is accomplished, it is then possible to transfer time-domain results to the frequency-domain with the use of FFTs and monitor the system’s stability by employing GNC. One of the significant advantages of the proposed method is its capability to define stability condition of the systems during operation and compare it with the instability borders to define an absolute and relative stability status of the system.

As aforementioned, the constant power nature of PECs with regulated output voltage might cause the instability of the PEDS due to the negative impedance at the terminals [1], [2], [6], and [26]. The proposed method investigates small-signal stability of the PECs through the AC interfaces inside the system. As was well-described in the impedance-based measurement techniques section, in order to measure generalized source/load impedances of a system in the AC interface, the system should be perturbed throughout a range of frequencies and the system’s response should be transferred to the $d-q$ reference frame. Generally, $d-q$ representation of the system facilitates stability analysis of the PECs through AC interfaces. This reference frame is used to convert sinusoidal variables into constant quantities.

In order to explain the concept and subsequently the mathematics of the proposed method, generalized Nyquist stability theorem is restated below. Considering the general
feedback system shown in Fig. 2 where \( G(s) \) and \( K(s) \) are a pair of multivariable systems, their linear behavior could be represented by the state-space equation:

\[
\frac{dX}{dt} = Ax + Bu \\
y = Cx + Du
\] (23)

Subsequently, the corresponding transfer function matrix \( T \) with inputs \( u \) and outputs \( y \) could be described as:

\[
T = C[sI - A]^{-1}B + D
\] (24)

Fig. 3 depicts a simplified model of a PEC with AC source/load through its AC interface and in the \( d - q \) reference frame. It is relatively straightforward to determine the terminal voltage \( V_{dq}(s) \) by utilizing basic circuit analysis techniques

\[
V_{dq}(s) = Z_{Ldq}(s)[Z_{Sdq}(s) + Z_{Ldq}(s)]^{-1}V_{Sdq}(s)
\] (25)

This equation represents the transfer function from source voltage to terminal voltage and can be simplified as

\[
V_{dq}(s) = [I + Z_{Sdq}(s)Y_{Ldq}(s)]^{-1}V_{Sdq}(s)
\] (26)

Back to the general feedback system, the output of the system shown in Fig. 1 may be expressed by the closed-loop transfer function

\[
y(s) = [I + G(s)K(s)]^{-1}G(s)u(s)
\] (27)

As it was discussed before, the small-signal stability of the closed-loop system (27) may be determined by directly studying the return-ratio matrix defined by

\[
L(s) = G(s)K(s)
\] (28)

By comparing (26) and (27), the voltage stability of the \( d - q \) frame model of a PEC with AC source/load, (26) may be determined by studying its return-ratio matrix through its AC interface.
Based on GNC, which was well-discussed in section II, the transfer function represented by (27) is closed-loop stable IFF the net sum of counter-clockwise encirclements around point \((-1+0j)\) by the set of characteristic loci of \(L(s) = G(s)K(s)\) is equal to the total number of RHP poles of \(G(s)\) and \(K(s)\). It is noteworthy to mention: for this system (Fig. 3), all the modes of the open-loop systems are assumed to be controllable and observable. By analogy (26), which can represent the transfer function of source voltage based on terminal voltage of general \(d-q\) model of a PEC, is stable if the roots of followed equation have negative real parts

\[
\det(1 + Z_{sdq}(s)Y_{ldq}(s)) = 0
\]  

(30)

This condition could be interpreted by Nyquist stability criterion to formulate a stability assessment of the PECs during the operational stage by preventing encirclements around point \((-1+0j)\) for the Nyquist diagram of \(Z_{sdq}(s)Y_{ldq}(s)\) in the complex plane. Furthermore, for the closed-loop systems, it could be utilized in combination with Middlebrook’s stability criterion to formulate Gain Margin (GM) stability criterion for the PECs. Although the GM stability criterion is a slightly conservative criterion, it is easier to implement. Basically, it restricts the Nyquist diagram of \(Z_{sdq}(s)Y_{ldq}(s)\) to lie within the unit circle in the complex plane. In this criterion, only GM of the systems is taken into account, regardless of the Phase Margin (PM) values. Therefore, the stability condition (30), driven from the AC interface of the interconnected source-load PEC, is a general stability condition in the \(d-q\) frame that depends on the stability criteria and the technique, it may address the stability of the PECs for both preoperational and operational stages with different degrees of the conservativeness.

In the proposed method, the general stability term, (30), is measured with the GNC in order to ensure the overall small-signal stability of the system and the results are compared with the GM criterion to illustrate the difference in degree of conservativeness and preciseness. Additionally, in order to find a return-ratio matrix of the system in a more convenient manner, some legitimate modifications and simplification are considered. In the literature, these simplifications are mainly considered in impedance measurement techniques for high power factor rectifiers [29]. Generally, the stability at the AC interfaces feeding PECs could be assessed with GNC by applying it to the return-ratio matrix \(L_{dq}(s)\) where it can be found by:
\[ L_{dq}(s) = Z_{sdq} Y_{Ldq} = \begin{bmatrix} Z_{Sdd}(s) & Z_{Sdq}(s) \\ Z_{sqd}(s) & Z_{sqq}(s) \end{bmatrix} \begin{bmatrix} Y_{Ldd}(s) & Y_{Ldq}(s) \\ Y_{Lqd}(s) & Y_{Lqq}(s) \end{bmatrix} \] (31)

Note that in the Middlebrook (and also GM) criterion, in order systems to be small-signal-stable, components of the return-ratio matrix have to lie within unit circle. In other words, according to (32), the magnitudes of the components should be less than one, regardless of their phases.

\[ |L_{dq}(s)| \leq 1 \]

\[ \therefore \left| \begin{bmatrix} Z_{Sdd}(s) & Z_{Sdq}(s) \\ Z_{sqd}(s) & Z_{sqq}(s) \end{bmatrix} \begin{bmatrix} Y_{Ldd}(s) & Y_{Ldq}(s) \\ Y_{Lqd}(s) & Y_{Lqq}(s) \end{bmatrix} \right| \leq 1 \]

\[ \therefore \begin{cases} |Z_{Sdd}(s)||Y_{Ldd}(s)| + |Z_{Sdq}(s)||Y_{Lqd}(s)| \leq 1 \\ |Z_{sqd}(s)||Y_{Ldq}(s)| + |Z_{sqq}(s)||Y_{Lqq}(s)| \leq 1 \\ |Z_{Sdd}(s)||Y_{Ldq}(s)| + |Z_{Sdq}(s)||Y_{Lqd}(s)| \leq 1 \\ |Z_{sqd}(s)||Y_{Ldd}(s)| + |Z_{sqq}(s)||Y_{Lqq}(s)| \leq 1 \end{cases} \]

(32)

In order to assess the stability of the PECs by GNC and by using the return-ratio matrix, some legitimate simplification has been considered in the proposed method. Fig. 6 depicts a standard AC interface of an SST; where the current injections (perturbations) and measurements take place. In [29] it was proven that for the high-power-factor multi-pulse rectifiers “all constant power load dynamics are reflected on the d – d channel”. Therefore, for high power factor PECs, it is acceptable to neglect all the other channels of input admittance \((Y_{Ldq})\) in the return-ratio matrix calculation. Consequently, the equation (31) is derived as:

\[ L_{dq}(s) \approx \begin{bmatrix} Z_{Sdd}(s) & Z_{Sdq}(s) \\ Z_{sqd}(s) & Z_{sqq}(s) \end{bmatrix} \begin{bmatrix} Y_{Ldd}(s) & 0 \\ 0 & Y_{Ldq}(s) \end{bmatrix} \approx \begin{bmatrix} Z_{Sdd}(s) Y_{Ldd}(s) & 0 \\ Z_{sqd}(s) Y_{Ldq}(s) & 0 \end{bmatrix} \]

(33)

\[ \approx \begin{bmatrix} i_1(s) & 0 \\ i_2(s) & 0 \end{bmatrix} \]
In addition, it was previously proven that the small-signal stability at the input terminals of the PECs is determined by the characteristic loci described by the eigenvalues of the corresponding return-ratio matrix, $L_{dq}(s)$. Given the input dynamics of the rectifier, the eigenvalues of $L_{dq}(s)$ at the AC interface are given by (33). Consequently, only the eigenvalue associated with the $d \rightarrow d$ channel (i.e., $l_1(s)$) can actually encircle the critical point $(-1 + j0)$, and thus be the cause of instability. The remaining eigenvalue associated with the $q \rightarrow d$ channel ($l_2(s)$) was shown to remain stationary at the origin of the complex plane and therefore be incapable of causing instabilities [27]. Therefore, in the proposed method, the Nyquist contour of $l_1(s)$ is determined and examined for the Nyquist evaluation.

The next crucial step is to define $l_1(s)$ from the model, which can be quite complicated. In the proposed technique, the current injection method [26] is used to define the return-ratio matrix of a PEC. In this method, the currents are injected through the AC interface of the system, with magnitudes of around 0.5% of the system’s current. The frequency of the injected current starts from 0 (DC component) and increases up to 1 kHz. This may be done by sweeping the frequencies in each test or chirp signal perturbation, which will be addressed in 4.3.1. The main reason for injecting current in a range of frequencies is to capture the system’s nonlinearities (as much as possible) through a linear model. Due to the varied frequencies, the injected currents are sinusoidal in the $d \rightarrow q$ synchronous reference frame with the frequency of the system.

Considering the signal injection methods utilized in the DC interfaces in [25] and [28], this method depicts similar behavior in the $d \rightarrow q$ synchronous reference frame with the system’s frequency of $\omega_s$. Furthermore, by utilizing FFTs in the model, it is possible to transfer time-domain results to the frequency-domain by obtaining magnitude and phase of the system’s responses to the perturbations. It is noteworthy to mention that, in the GNC technique, the complete Nyquist contour of $l_1(s)$ in the s-plane is considered unlike the unit circle criterion (or Middlebrook criterion) used in [38]; which solely consider the magnitudes of the components of the return-ratio matrix (according (32)). Therefore, in order to achieve the Nyquist contour, the phase of $l_1(s)$ should be obtained from the model in addition to the magnitude. The main advantage of addressing GNC for the small-signal stability assessment of the PECs is that it eliminates the artificial conservativeness in the investigations.
In other words, by utilizing the unit circle criterion, systems with a return-ratio magnitude greater than unity are considered to be unstable systems, even though they might be still stable considering phases of the return ratio. Fig. 11 illustrates algorithm and flowchart for the proposed small-signal stability analysis technique based on impedance measurement technique and GNC.
The proposed method in this research takes phase of the return-ratio into account in addition to magnitude, and it enhances the degree of accuracy of the method by diminishing the degree of the conservativeness. Therefore, the $l_1(s)$ contour in the s-plane can be sketched by

$$l_1(s) = Z_{sdd}(s)Y_{ldd}(s) = |l_1(s)| \sin \angle l_1(s) + j|l_1(s)| \cos \angle l_1(s)$$

(34)

In the model validation section, the difference between degree of conservativeness and accuracy of the GM and proposed technique is shown by a sample stability analysis test case in which the results from unit circle criterion shows an unstable system. However, this same system is also shown to be stable in the time-domain simulation and proposed method based on GNC verifies this fact as well. Fig. 11 depicts different stages and algorithm of the proposed small-signal stability technique.

4.2 Practical considerations to accomplish requirements for the proposed method

In this section, in order to verify proposed technique, an average value model of a SST [37] is used. The STT model and all the blocks required to achieve the return-ratio matrix and its contour in the s-plane are developed in simulation platform (i.e. PSCAD or RSCAD). The proposed method in this research is based on an impedance measurement technique and a shunt current injection method for use with non-real-time applications as well as parallel perturbations for real-time applications, when utilizing shunt current injection for the source side and series voltage injection for the load side. In the shunt current injection method, the perturbations are made by injecting current into the systems with the shunt current source. In the series voltage injection method, the system is perturbed by voltage source series with load.

For the non-real-time applications and on the PSCAD platform, in order to achieve required data for the proposed small-signal stability method, the first step is to perturb the system in a range of frequencies; this has been done with the “injection current harmonics” block of PSCAD. Basically, this part is for perturbing the system in a range of frequencies. The harmonic current magnitude is about 0.5% of the fundamental current magnitude and its frequency is in a range of 0-1000 Hz, with an increment of 5 Hz. In other words, the injections are more than 15th harmonics of fundamental frequency. The system’s voltages are measured in the source and load sides of the system (Fig. 6). Subsequently, by utilizing a single-phase Phase-Lock-Loop (PLL), the system’s phase is obtained and utilized to transfer load/source voltages and currents from
synchronous reference frame to the $d$-$q$ reference frame. FFT analysis to transfer time-domain data to frequency-domain data is accomplished with an on-line frequency scanner. The base frequency for the FFT was 60 Hz and it captured up to 16th harmonics. Furthermore, the magnitude of the output is in RMS and the phase is in Radians. Using the FFT’s outputs and based on (6)-(9), it is possible to find the source impedance and load admittance matrices, $(Z_{sdq}(s)$ and $Y_{ldq}(s))$, in the $d$-$q$ reference frame. The small-signal stability technique proposed in [38] was solely utilized magnitudes of the source and load impedances and came up with the criterion based on return-ratio magnitude (unit circle criterion). This criterion ensures the small-signal stability of the system while the magnitude of $l_1(s)$ (the $d$-$d$ channel of the return ratio) is less than one. This criterion slightly enhances the degree of conservativeness in the small-signal stability assessment. For instance, a system with $l_1(s)$ greater than the unit circle that never encloses -1+j0 point is considered to be unstable by this criterion, whereas in reality, this system is actually stable. This is due to the fact that this criterion restricts the Nyquist contour of the return-ratio in the unit circle, whereas in the generalized Nyquist theorem, the Nyquist contour for stable cases shouldn’t encircle -1+j0 point. It is obvious that by preventing Nyquist contour of the return-ratio to pass unit circle, it will never encircle -1+j0 point and the system will remain stable. In the new proposed criterion, the phase of the return-ratio is also taken into the account, meaning that in addition to the magnitude, by considering the phase, the Nyquist contour of the system can be obtained by (34). This will assist in finding more precise results with less conservativeness in the system’s stability assessment. In the following section, several case studies are analyzed and it is shown that by utilizing the GNC of $l_1(s)$, the stability of the case is well-studied in all different conditions.

Furthermore, even though this method utilizes FFT blocks, which are linear devices in nature, to extract and analyze the signal and the NLAM of the SST is used, based on the proposed methods in [7] and [8], perturbing the systems in a range of frequencies can take some part of the nonlinearities of the systems into account. Since the system was perturbed in a range of frequencies and different operating points were studied, nonlinearities of the system is taken into account to some extent.

The algorithm for the proposed method is based on perturb-and-observe algorithm, similar to most impedance measurement-based methods. The system’s perturbations are “shunt
current injected” and therefore the voltages are measured as a system’s response. Subsequent to measuring perturbations and the system’s responses in the synchronous reference frame with utilizing d-q transformation, source and load d-q voltages/currents are calculated. At this point, the magnitude and phase values for each voltage/current are found with an FFT. Subsequently, these values could be utilized to define source/load impedances, in order to be utilized for the Nyquist criterion and contour map.

4.3 Additional considerations in order to enable real-time capability of the proposed technique

4.3.1 Chirp excitation signals

Chirp signals, also known as swept-sine signals, are a common wide-bandwidth signals used to perturb the system for impedance measurement [39]. This dissertation proposes using chirp signals for perturbation in the impedance measurement, thus simultaneously enabling real-time capability and nonlinearity consideration of the proposed model.

For chirp signals, the instantaneous frequency changes as a function of time. Therefore, it is possible to perturb systems in real-time throughout a range of frequencies. The following shows the linear chirp form of the perturbation signal:

\[ x(t) = A \sin(2\pi(f_0 + (f_1 - f_0)t/2T)t) \]  

(35)

Where \( x(t) \) could be the voltage and/or current signal, depending on the type of perturbation (series voltage and/or shunt current), \( A \) is the magnitude of the perturbation, \( f_0 \) is the start frequency, \( f_1 \) is the end frequency, and \( T \) is the duration of the chirp signal (for real-time applications, the chirp signal is periodic and \( T \) should be reset after reaching final value).

Utilizing chirp signals to perturb a system for impedance measurement purposes facilitates perturbation of the system in a range of frequencies and in real-time simultaneously. In other techniques, in order to be able to perturb systems in a range of frequencies, the test system must be perturbed separately at each single frequency, thus preventing those techniques to be applicable for real-time applications.
4.3.2 Parallel perturbations

In order to obtain the source and load impedances of a test system, perturbation is required. As previously discussed, the two types of perturbations are shunt current injection and series voltage injection [40]. The source impedances can be measured more accurately by the shunt current injection method, due to the fact that, in a normal system, since stiff output characteristic of source is preferred, source impedance is much lower than load impedance. Thus, most of the shunt current injection flows into the source side and the load side is only slightly perturbed. Conversely, series voltage injection is appropriate for load impedance measurements. Generally, in order to perturb the load side in such systems, two solutions are available: first, the insertion of a filtering impedance, which modifies the system configuration and changes the load impedance (our goal is to develop a technique to assess the stability of a PEC without changing its characteristics); second, the perturbation of the load with the series voltage injection. With the second solution, most of the injected voltage affects the load side for the same reason for the shunt current injection and considering the fact that admittances are taken into account (instead of impedances) and source admittance is much higher than load admittance).

In literature, one of these perturbation techniques would typically be used and the desired impedance was calculated based on the perturbations and system’s responses. Afterward, with source and load impedances, stability of system was studied. However, in the proposed technique, both source impedance and load admittance is calculated at the same time in order to be able to assess the stability of a system in real-time. This method is referred to as parallel perturbations in this dissertation. In order to measure the system impedance by parallel perturbations, the magnitude of the injected current and voltage (A in (35)) should be between 0.5% to 1% of the system’s current and voltage at the same node. With this condition held true, the power of the perturbation is enough for an appropriate measurement and the system’s operation point is not changed due to high perturbation power.
CHAPTER 5
MODEL VALIDATION AND SAMPLE STABILITY ANALYSIS IN SIMULATION

5.1 Test system configuration

In this section, the small-signal stability of a sample PEC is studied and well-discussed for both stable and unstable conditions. The stable situation, itself, can be divided into asymptotic and marginal stability. Herein, in order to illustrate the capability of the proposed technique to address the small-signal stability condition of the systems, all three possible types of stability are studied with the test system and by instantiating three different case studies. In addition, the results for the impedance measurement-based method with utilizing unit circuit criterion, which solely considers the GM of the return-ratio, are shown and discussed.

In this study, a sample PEC is modeled with the SST connected to the source and load. The schematic of the 1st generation SST, with the source-load interface utilized for the proposed small-signal stability analysis, is illustrated in Fig. 12. Stability of the system is investigated through the AC interface inside the SST. Furthermore, in order to facilitate model verification, the average value model of a SST [37] is used. The test bed, SST model, and also stability analysis blocks are developed in PSCAD.

Fig. 12. Schematic of the 1st generation SST used as a sample PEC with the source-load interface
One of the most significant advantages of proposed small-signal stability technique over other aforementioned techniques in the previous studies is its capability to address the small-signal stability of the systems while they are operating. This could be extended to real-time stability assessment of the PEDS. Furthermore, the return-ratio matrix may be utilized as an indicator of stability which depicts the margin of the system to the instability boarders. Therefore, by extension of this method to the real-time applications, the stability of the PEDS can be comprehensively studied during their operation.

5.2 Proposed method results for PSCAD platform and in non-real-time

5.2.1 System with asymptotic stability

In order to validate the method in the stable conditions, a single phase SST is connected to the ideal source from primary side and a RL load is connected to the secondary side of the SST (Fig. 12). The high-voltage and low-voltage levels of the SST are 7.2 (kV) and 120 (V) respectively and 1.534+j0.753 (Ω) is the initial load of the system. The simulations runtime is 7 (s) with 50 (µs) time-steps. The time-domain simulation results for RMS voltage, current, active and reactive powers in Fig. 13 demonstrate that the system is stable.

![Fig. 13. Time-domain results for the asymptotic stable SST connected to the RL load: (a) and (b) RMS values for the voltage and current of the secondary side; (c) and (d) active and reactive powers.](image)

Furthermore, actual time-domain simulation results, voltage and current, with the stability assessment result based on unit circle criterion (developed in [38]) are shown in Fig. 14.
(a) - (b). On the other hand, the magnitude of the d – d component for the return-ratio matrix \((l_1(s))\) is illustrated in Fig. 15. Based on Nyquist evaluation, the system is stable under this loading condition since \(|l_1(s)| < 1\) and the Nyquist contour does not encircle point \(-1+0j\). We can also conclude from Fig. 14 that the system is far away from instability margin, since the magnitude of the \(l_1(s)\) component of the return-ratio matrix is significantly less than 1.

Fig. 14. Simulation results for the asymptotic stable SST connected to the RL load: (a) and (b)
Actual values for the voltage and current of the secondary side in time-domain

Fig. 15. Proposed stability metric showing the relative stability of the test bed for asymptotic stability

5.2.2 System with marginal stability

To further study how the proposed stability technique behaves in sensitive and critical situations, the RL load connected to the test system is reduced to 10% of its initial value. The
RMS values for voltage, current, active and reactive power are illustrated in Fig. 16 reveal that the system is still stable for this loading condition.

![Time-domain results for the test system with the marginal stability](image)

**Fig. 16.** Time-domain results for the test system with the marginal stability: (a) and (b) Secondary side RMS voltage and current; (c) and (d) active and reactive powers

In addition, as illustrated in Fig. 17 (a), the peak-to-peak value for the low voltage side of the SST hold constant at 240 (V). Fig. 17 (b) depicts that this loading condition leads the current of the LV side of the system to increase by factor of 10 and subsequently, causes the test system to become closer to the instability margin. The marginal stability condition in the proposed technique and with the unit circuit criterion may be interpreted by the magnitude of the $d - d$ component in the return-ratio matrix, $l_1(s)$. In other words the system is marginally stable while $|l_1(s)| = 1$. 

![Additional plots](image)
Fig. 17. Simulation results for the marginal stable test bed: (a) and (b) Time-domain results for the voltage and current of the secondary side.

Fig. 18 shows the magnitude of the \( l_1(s) \) component of return-ratio matrix which verifies the stability of the system in this condition. Although \( l_1(s) \) doesn’t pass critical line of \( y = 1 \), its magnitude is close enough to unity that it can be interpreted as a marginal stability based on generalized Nyquist and relative stability concepts.

![Graph showing stability criterion](image)

Fig. 18. Proposed stability criterion for the marginal stable test system

5.2.3 Small-signal stability analysis of the test bed by gradual decrement in load that cause instability

As described above, based on GNC, a system is unstable when the Nyquist contour of the return-ratio matrix encircles point \(-1+0j\). This fact can be interpreted by the unit circle criterion that the magnitude of the return-ratio is greater than 1. In this test case, the RL load connected to the SST is gradually decreased to 1% of its initial value while the system is operating. As discussed previously, since an SST is a constant voltage device, this reduction in load causes a power increase in the test bed. This gradual change in the load is made by a slider connected to the variable RL load in the model and it causes system’s instability after almost 2.2 (s). The system’s stability status is monitored in real-time and the results are saved and shown below. As is shown in Fig. 19 the RMS values for the voltage, current, active, and reactive power clearly...
depict that complete instability, as a result of a system breakdown, occurs after approximately 2.2 (s) of simulation as a result of the change in RL values during the real-time simulation.

![Simulation results in time-domain for the unstable test system](image)

**Fig. 19. Simulation results in time-domain for the unstable test system:** (a) and (b) rms voltage and current in LV side of the SST; (c) and (d) active and reactive powers

The RMS values for the voltage, current, active and reactive power in Fig. 19 clearly depict that the complete instability, and as a result systems breakdown, occurs in this loading condition in the system. This fact is shown by mapping the magnitude of the d – d channel of the return-ratio matrix, \( l_1(s) \), in Fig. 20. In simulation, this value exceeds the critical line \( y = 1 \) in almost 2.2 (s) due to the change in the loading condition of the test bed.

In fact, it can be seen that the system’s instability in the time-domain occurs simultaneously with crossing the \( |l_1(s)| \) loci and line \( y = 1 \).
Fig. 20. Stability metric (unit circuit stability criterion) showing the test system becoming unstable

5.3 Proposed method results for GNC in PSCAD platform and non-real-time

In this section, the small-signal stability of the test bed described in section 5.1 and Fig. 12 is investigated through GNC. Based on theory and (34), GNC doesn’t have any artificial conservativeness for assessing small-signal stability of PECs and/or PEDS; whereas the unit circle criterion has some degree of conservativeness, which is as a result of solely considering the gain of the return-ratio matrix in this criterion. In the GNC, the phase of return-ratio matrix is taken into account as well as its gain. This feature helps to eliminate all the artificial conservativeness for small-signal stability analysis. In order to be able to compare the capabilities of GNC over the unit circle criterion, the same test cases and loading conditions are implemented and the results are compared for all three stability cases (asymptotic stable, marginal stable, and unstable).

5.3.1 Results for asymptotic stable system and based on GNC

In order to validate the method with GNC during stability, the test bed described in section 5.1 is connected to the same source and RL load as in 5.2.1. Since the system’s configurations and loading have not changed, the time domain simulation results are the same as Fig. 14. Furthermore, the Nyquist contour of the \( d - d \) component for the return-ratio matrix, \( l_1(s) \), is illustrated in Fig. 21. Based on the Nyquist evaluation, the system is stable under this loading
condition, since the Nyquist contour does not encircle point \(-1+0j\). From the Nyquist map, it is evident that the system is far away from instability margin, since the \(|l_1(s)|\) component of the return-ratio matrix is significantly less than 1.

![Nyquist Contour](image)

**Fig. 21.** Nyquist plot for the asymptotic stable test bed in s-plane

### 5.3.2 Stability analysis of the test bed with marginal stability and through GNC

For the test case described in 5.2.2, the return-ratio contour of the \(l_1(s)\) component in the s-plane is shown in Fig. 22. Return-ratio contour for the marginal stable system in s-plane. Although \(l_1(s)\) doesn’t encircle critical point of \(-1+0j\), its magnitude is so close to unity that it can be interpreted as marginally stable based on GNC. The marginally stable condition in the proposed technique may be interpreted by the magnitude of the \(d - d\) component in the return-ratio matrix \((l_1(s))\). In other words, the system is marginally stable while \(|l_1(s)|\) is less than and close to 1.
5.3.3 **GNC and small-signal stability investigation of unstable system**

In this section, the experiment from 5.2.3 is repeated with some modifications. Instead of a gradual decrement in the loading condition, the system was loaded with 1% of its initial value from start. This helps to analyze the test case and discuss the results precisely.

As previously stated, based on the unit circle criterion for the systems with the magnitude of $Z_{sd}(s)\cdot Y_{ld}(s)$ in the return-ratio matrix greater than one, the system is unstable. Moreover, this instability condition was interpreted with the GNC by encirclement of point $-1+0j$ by the Nyquist contour of the return-ratio. In this test case, the RL load connected to the SST decreased to 1% of its initial value. It causes the instability in the system at the beginning of the simulation that could be observed from time-domain data shown in Fig. 23. Sinusoidal voltage and current waveforms in Fig. 23 clearly reveal the complete instability and the resulting breakdown in system.
Fig. 23. Test bed in the unstable condition: (a) and (b) Time-domain results for the totally disordered voltage and current of the LV side

This fact is shown by Nyquist contour of the $l_1(s)$ in Fig. 24 as well, which even though its magnitude is greater than unity, it does not encircled the -1+0j point in the first 2 (s).

Fig. 24. Return-ratio plot in s-plane for unstable test system

In fact, the earliest encirclement by the Nyquist contour occurs simultaneously with system’s instability in the time-domain. This capability, which considers the phase angle in
addition to magnitude, is the dominant advantage of the GNC over unit circle criterion. As Fig. 25 displays with the unit circle criterion (GM criterion), which solely considers magnitude of the return-ratio, the system is diagnosed as unstable from the beginning, since the return-ratio magnitude is greater than unity.

![Graph](image)

Fig. 25. Unit circuit stability criterion (for the unstable case the value of return-ratio is greater than one)

### 5.4 Developed test system in RSCAD and simulation results for the proposed technique in real-time

In order to study the proposed technique for real-time applications, a new test system is developed in Real time Simulator Computer Aided Design (RSCAD). The Center for Advanced Power Systems (CAPS) in Florida State University has a great capability for real-time simulation and co-simulation. The simulator room (Fig. 26) in CAPS has 14 RTDS racks, which make this center one of the largest and most unique RTDS centers of the world.
The developed test system in the RTDS platform is a modified version of the IEEE-34 bus test system [41] on the RSCAD platform. The IEEE-34 bus test system is a 24.9 kV feeder; whereas the voltage level in the developed test system is scaled down to 12.47 kV. Although the voltage is scaled down, overall load of the system remains the same. The schematic of the IEEE-34 bus test system, with integration of the SSTs in a distribution level, is shown in Fig. 27. In this test system, all the loads in the original IEEE-34 were connected to the system through an SST. Basically, this system represents a small-scale PEDS. Furthermore, for the test system under study, in order to diminish computations in the developed model in RSCAD platform (to be able to develop a model in a single rack of RTDS), all the loads after bus-812 are replaced with the cumulative load at bus-812. There are (10kW+j5 kvar) and (15kW+j7.5 kvar) loads connected to SST1 (phase a) and SST2 (phase b) respectively. For the test cases in this section, the load in SST2 remains constant and by changing load in SST1, the stability of PEC is studied via the proposed technique and in real-time. Moreover, some modifications are proposed in section 4.3 (and its subsections) in order to enable real-time capability of the proposed technique that will be discussed broadly in the next subsection.
5.4.1 Test system configuration modifications in order to enable real-time capability

In this section, in order to verify the proposed technique, the average value model of a SST [37] is utilized in the abovementioned test system. The STT model, as well as all the required blocks to achieve return-ratio matrix in real-time, are developed in the Real Time Digital Simulator (RTDS). In this section, the small-signal stability of a sample PEC is studied and well-discussed for different loading conditions that lead the system into both stable and unstable conditions. Herein, a sample PEDS is modeled with the SST connected to the source and load (Fig. 28) and stability of the system is investigated through the AC interface inside the SST. One of the most significant advantages of the proposed stability technique over other developed techniques is real-time capability. This capability is enabled by utilizing chirp signal excitation (4.3.1) and parallel perturbations (4.3.2) in the proposed technique and employing RTDS to develop the test system and stability technique in hardware development and experimental implementation part.
Fig. 28. Schematic of a SST used as a sample PEC with perturbations in source and load interfaces simultaneously (in order to enable real-time capability)

Utilizing chirp signals to perturb systems for impedance measurement purposes facilitates to perturb systems for a range of frequencies and in real-time simultaneously. In other techniques, in order to be able to perturb systems throughout a range of frequencies, the test system must be perturbed for each single frequency thus preventing those techniques to be applicable for real-time applications. Furthermore, parallel perturbations facilitate the data acquisition process for source impedance and load admittance concurrently. As was well-discussed previously in 2.4 and 4.3.2, any power distribution system can be modeled as an interconnected source-load system. In a normal source-load system, stiff output from the source is desirable. In other words, source impedance should be insignificant compared to load impedance and the system’s overall impedance. This means that by using shunt current injection on the source side for perturbing the systems, it is that likely all of the injected current will affect and stimulate the source part and that the resulting responses to the perturbations may be utilized to calculate source impedance. Similarly, in a stiff system, series voltage injection from the load side is mostly perturbs the load of the system, meaning that the system’s responses to these perturbations may be utilized to calculate load impedance (or admittance).

On the other hand, applying this technique to the RTDS platform enables real-time capability for hardware development and experimental implementation. Furthermore, the magnitude of the return-ratio matrix may be employed as an indicator of stability, which can define the margins between instability borders for the systems under study, as well as the system’s relative stability. Therefore, by taking advantage of proposed technique, the stability of the PEDS can be comprehensively studied in real-time.
5.4.2 Instantiated test scenarios to study small-signal stability of the SST under different loading conditions and in real-time

In order to study the developed test system in the RTDS platform, different scenarios are instantiated in this research and the results are analyzed. In the first test scenario, the test system operates in its normal loading condition. This means two loads of (10kW+j5 kvar) and (15kW+j7.5 kvar) are connected to SST1 (phase \(a\)) and SST2 (phase \(b\)) respectively. The simulation results for these loading conditions are shown in Fig. 29. As is illustrated in this figure, the magnitudes of the \(d-d\) channel of the return ratio matrices \(L_{dd}\) for both SSTs are less than unity, which ensures stability of the SSTs in the system. Furthermore, RMS load voltages and currents are shown along with the SSTs’ active power for this condition.

![Fig. 29. Simulation results in RSCAD for (a) SST1 and (b) SST2 in their normal operation](image)

In the second test scenario, the \(R\) and \(L\) values for the variable RL load connected to the SSTs are increased thus due to the constant voltage output nature of the SST consumed power is reduced. As was described previously, a SST is a constant voltage device at its output terminals. The increment in the \(R\) and \(L\) values leads to decrement in the total power of the test system (it is...
accurate to interpret this as load shedding condition in this terminal) and are made by step changes in the variables. The values of the R and L for both SSTs are shown in Table 1. Furthermore, the corresponded simulation results, i.e. the active power of the SST, the RMS load current and voltage, and the unit circle stability criterion for both SSTs are shown in Fig. 30.

### Table 1: R and L values connected to the SSTs for the power decrement scenario

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>SST 1</th>
<th>SST 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R (Ω)</td>
<td>L (mH)</td>
</tr>
<tr>
<td>0-10</td>
<td>4.45</td>
<td>5.81</td>
</tr>
<tr>
<td>10-20</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>20-30</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>30-40</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>40-50</td>
<td>60</td>
<td>140</td>
</tr>
</tbody>
</table>

![Fig. 30. Real-time simulation results for the RSCAD test system under load shedding condition for (a) SST1 and (b) SST2](image)

As was shown in Fig. 30, the unit circle stability criterion ($L_{dd}$) for both SSTs remain less than unity, meaning both SSTs are in the stable region during these operating points. By analyzing the real power of each SST, it is evident that in this test case, each SST operates under its nominal operating point. This claim is substantiated by the $L_{dd}$ graphs.
The final test scenario used to study the SST’s stability under different loading conditions in real-time occurs while the value of the RL loads connected to the SSTs decline. As a result, and based on regulated output voltage characteristics of SST, the power drawn by the SST increases to the point of making the test system unstable. The load decrement for this test scenario is also made by the step changes in the $R_s$ and $L_s$ at 10 (s) time intervals.

In this test scenario, in order to be able to study effects of unstable SSTs on the PEDS and other PECs (i.e., SSTs), load increments for each SST is made individually while the other SST experiences a load shedding situation, which is fully stable based on previous test case. This helps us to distinguish influences of unstable SSTs on stable PEDS and PECs. Table 2 illustrates the Rs and Ls changes for both SSTs in this scenario (decrement for the SST 1 and increment for the SST 2 values). The unit circle stability criterion for this test case during the load changes is shown in Fig. 33, along with the SSTs’ power and RMS load current and voltage.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>SST 1 R (Ω)</th>
<th>SST 1 L (mH)</th>
<th>SST 2 R (Ω)</th>
<th>SST 2 L (mH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>4.45</td>
<td>5.81</td>
<td>3.01</td>
<td>3.80</td>
</tr>
<tr>
<td>10-20</td>
<td>0.445</td>
<td>2.5</td>
<td>6</td>
<td>9.50</td>
</tr>
<tr>
<td>20-30</td>
<td>0.0445</td>
<td>0.5</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>30-40</td>
<td>0.0225</td>
<td>0.275</td>
<td>28.8</td>
<td>60</td>
</tr>
<tr>
<td>40-50</td>
<td>0.01536</td>
<td>0.0271</td>
<td>56</td>
<td>120</td>
</tr>
</tbody>
</table>

As is evident from Fig. 31 (a), SST 1 becomes unstable by increasing the SST’s load. In the active power plot, it is illustrated that once SST 1 becomes unstable; the active power cannot converge to specific value. The $L_{dd}$ plot confirms this fact and the load increase for SST 1 causes increment of the unit circle criterion to the point that it reaches (and passes) the critical value of 1, resulting in the system becoming unstable.
The interesting fact in this study is the behavior of the SST 2 when under this condition. Based on the second test scenario, it is expected that SST 2 would operate in the stable region, since it experiences the load shedding condition (similar to the second test scenario). From the power, current, and voltage plots, this fact is evident. The only difference between Fig. 30 (b) and Fig. 31 (b) is the $L_{dd}$ plot, which in Fig. 31 (b), the unit circle criterion exceeds 1. Even though the SST 2 is stable, the PEDS is unstable and the developed stability criterion depicts this. In fact, the proposed/developed stability criterion has the capability to determine systems’ small-signal stability regardless of the stability of the PEC.
Furthermore, the $l_1(s)$ contour in the s-plane is sketched based on (34) in Fig. 32. As is shown, the Nyquist contour encircles the point -1+j0. In fact, the first encirclement of point -1+j0 by the Nyquist contour occurs when the system becomes unstable. In the real-time demo this fact is observable.

In the second step of the final test scenario, the same strategy as the first step (load decrement for one SST and load increment for another) is instantiated. The only distinction herein is that SST 1 experiences load shedding condition (and is stable); whereas SST 2 load increases. Table 3 illustrates the $R_s$ and $L_s$ changes for both SSTs in this scenario (incremented for the SST 1 and decremented for the SST 2 $R_s$ and $L_s$ values). The unit circle stability criterion for this test case during the load changes is shown in Fig. 33 with the SSTs’ power, RMS load current, and RMS load voltage.

**Table 3: Values for R and L connected to the SSTs for load decrement in SST 1 and load increment in SST2**

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>SST 1</th>
<th>SST 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R$ (Ω)</td>
<td>$L$ (mH)</td>
</tr>
<tr>
<td>0-10</td>
<td>4.45</td>
<td>5.81</td>
</tr>
<tr>
<td>10-20</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>20-30</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>30-40</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>40-50</td>
<td>60</td>
<td>140</td>
</tr>
</tbody>
</table>
Based on the unit circle criterion ($L_{dd}$) shown in Fig. 33 (b), SST 2 becomes unstable by increasing the SST’s load. It is illustrated in the real power plot for SST 2 that after it becomes unstable, the real power of the SST cannot converge. Furthermore, by studying the SST 1 active power, load current, and voltage plots, it is evident that SST 1 operates in the stable region (since it experiences the load shedding condition). The only difference between Fig. 30 (a) and Fig. 33 (a) is in the $L_{dd}$ plot, which in the Fig. 33 (a) it is shown to exceed the critical line $y=1$. Although the SST 1 in this test case is stable, the system is unstable (due to the SST 1 instability) and the proposed stability criterion distinguishes this fact.

![Fig. 33. Real-time simulation results for the RSCAD test system while (a) SST 1 sheds the load and (b) SST 2 increases the load](image)

Moreover, the $l_1(s)$ contour for the SST 2 in this loading condition is sketched in the s-plane, based on (34) in Fig. 34. As is shown, the Nyquist contour encircles point $-1+j0$. In this figure, it is not obvious when the first encirclement happens, since system’s instability is simultaneous with the first encirclement. However, in the real-time demo, this fact is observable.
Fig. 34. GNC for the SST 2 in RSCAD test system under load increment condition for SST2
CHAPTER 6

HARDWARE DEVELOPMENT AND EXPERIMENTAL IMPLEMENTATION

Hardware development and experimental implementation to measure source and load impedances in real-time and utilize them to find return ratio matrix and as a result stability criterion in real-time is explained in this chapter. This chapter is divided into the following subsections: the design and development of a test bed to achieve real-time small-signal stability analysis with the proposed criteria and methods and a study of the developed test bed’s small-signal stability under different loading conditions using source and load impedance measurements and the proposed stability assessment criteria. Based on our lab capabilities, it is possible to reproduce in hardware part of the test system described in 5.4 and have the rest of the system modelled in the RTDS. This experiment is called Power Hardware-in-the-Loop (PHIL). The RTDS Simulator has been successfully used for performing PHIL experiments in a wide range of applications, e.g. testing of motors of electric ships and motor drives even at the kW and MW ranges [42]. Specifically, PHIL simulation is a relatively novel tool in studying the integration of Distributed Energy Resources (DER) in the transmission and distribution grids. Photovoltaic panels, wind turbines, electric vehicles or entire micro grids can be connected to simulated active networks containing various simulated DER devices. To date, PHIL simulation has been successfully used in this field and it is expected to gain high interest in the future.

In this research, in order to implement the PHIL experiment illustrated in Fig. 35, the developed test system model in the RTDS platform (described in 5.4) and the Nonlinear Dynamic Loads (NLDL) test bed are employed. The NLDL test bed is a primary tool in our lab that can be utilized for this experiment. The main part of hardware development can be implemented by the converters in the NLDL test bed. The variable AC load is the only part of the hardware development not part of NLDL test bed. This section is followed by concise introduction to the NLDL test bed in 6.1, describing IMU implementation via PHIL experiment in 6.2 and detailing results for small-signal stability analysis of the developed PHIL experiment in 6.3.
Fig. 35. PHIL experiment schematic to study small-signal stability of the test system in real-time

6.1 NLDL test bed

The NLDL test bed consists of two identical racks, each including a three-phase transformer, a two-level Active-Front-End (AFE) rectifier, a two-level inverter, a three-level Neutral-Point-Clamped (NPC) rectifier, and two DSP boards. The NLDL test bed configuration is illustrated in Fig. 36.
6.1.1 Introduction to back-to-back/3-phase/2-level converters in the NLDL test bed

Recent development of power flow controllers based on power electronics-based converters has improved the control of the active and reactive power flow in PEDS. The most frequently used topology to achieve these tasks is an AC-to-DC rectifier followed by a DC-to-AC inverter, connected through a DC bus; this topology is known as Back-to-Back (BTB) converter [43]. Typically, the BTB converter is used to exchange active power between two AC systems. The active power can freely flow in both directions, from one AC system to the other one, as long as the DC bus voltage is properly regulated. Also, the BTB converter connected in shunt to an AC power system can be used as a Static Synchronous Compensator (STATCOM), in order to compensate reactive power and current harmonic distortion; therefore, it is also called BTB-STATCOM [43]. Basically, the BTB converters provide independent reactive power compensation. In some research, the BTB converter is used to compensate current harmonic
distortion due to unbalanced and distorted grid voltage conditions. Unbalanced and distorted grid voltage mostly happens as a result of grid-connected PWM converters with LCL filters.

The first stages of the BTB converters (AC-to-DC rectifier) have been developed in the NLDL test bed is shown in Fig. 37. The distinguishing characteristics of this stage are as following:

- Power factor correction on input current possible
- Output DC voltage higher than peak of input line-line voltage (boost rectifier)
- Capable of bidirectional power flow
- Provides DC voltage on C1 for inverter
- Controller utilizes a phase-locked loop to track the phase angle of input voltage for transforming variables to synchronous $d$-$q$ reference frame

![Fig. 37. 3-phase boost rectifier](image)

The distinguishing characteristics of the second stage (DC-to-AC inverter) of the BTB converter developed in the NLDL and shown in Fig. 38 are as follows:

- Capable of bidirectional power flow
- Capable of synthesizing AC sine waves from DC voltage on C1
- In order to achieve previous step, it utilizes pulse-width modulation (PWM)
- Open-loop PWM still uses a voltage sensor for DC voltage on C1 to scale the reference voltage to produce a duty cycle for the PWM comparator
- Closed-loop control can utilize current and voltage feedback to improve output voltage performance
- Capable of utilizing two of the half-bridges to make an H-bridge for creation of a DC-DC converter for 0-Vdc DC output

Fig. 38. 3-phase inverter (a) schematic (b) in the NLDL test bed

6.1.2 Introduction to 3-level Neutral-Point-Clamped (NPC) converter

Recently, implementation of multilevel converters for medium and high power/voltage applications has significantly increased. Among various well-known multilevel converter configurations, i.e., the neutral-point clamped (NPC), flying capacitor, and cascaded H-bridge, the three-level NPC converter has been widely accepted and investigated for various applications
Several Pulse Width Modulation (PWM) strategies have been proposed and extensively investigated for the 3-level NPC converter to achieve the following main objectives:

1. To carry out the voltage-balancing task of the dc-link capacitors, which is the main technical challenge of the NPC converter;
2. To eliminate the low-frequency oscillations of the neutral point (NP) voltage, which appear under certain operating conditions and if not mitigated, impose stress on the converter components.

The proposed PWM strategies for a three-level NPC converter are mainly classified into carrier-based PWM (CB-PWM) and space-vector modulation (SVM) strategies. The CB-PWM strategies are mostly based on pure sinusoidal PWM (SPWM), or a SPWM strategy in conjunction with a zero-sequence voltage injection. Compared with the SPWM strategy, inclusion of a zero-sequence voltage extends the linear-modulation range of the converter [44]. The 3-level NPC converter in the NLDL test bed (Fig. 39) has been developed based on CB-PWM strategy with zero-sequence voltage injection.

![Diagram of NLDL test bed 3-level NPC converter](image)

**Fig. 39.** Schematic of the NLDL test bed 3-level NPC converter (courtesy of NLDL test bed tutorial)

### 6.1.3 PLECS model of the NLDL test bed

In order to be able to make changes in the NLDL test bed and the test modified system prior to any hardware experiment, a PLECS model of the NLDL test bed was developed in the Energy Conversion and Integration (ECI) Thrust group. This model helped to simulate test
systems with the full-switching model of the test bed prior to experiment implementation, ensuring the model worked properly and that results were desirable. The PLECS models for back-to-back 3-phase 2-level converters in the NLDL test bed (described in 6.1.1) and 3-level NPC converter (described in 6.1.2) are shown in Fig. 40 and Fig. 41, respectively.

Fig. 40. PLECS model of back-to-back/3-phase/2-level converters in the NLDL test bed

Fig. 41. PLECS model for 3-level NPC converter in the NLDL test bed
In this research, in order to modify the NLDL test bed and conduct PHIL experiment, the PLECS model was initially modified and the results are analyzed and studied. The primary results from modified PLECS model for the PHIL experiment is described and analyzed in the result section of this chapter.

6.2 Impedance Measurement Unit (IMU) implementation via PHIL

Impedance Measurement Unit (IMU) can be utilized to measure source impedance and load impedance of a PEC. In order to develop hardware experiment to test and verify the proposed technique for small-signal stability analysis of the PECs in real-time, an IMU capable of measuring and computing the source/load impedances in real-time is required. Basically, this unit must be capable of perturbing the test system continuously, and capturing required data from it in real-time. Furthermore, it is required that the system be able to accomplish all the computations in real-time. In other words, the computations for finding source and load impedances, and as a result investigating small-signal stability of the under test system, has to be accomplished in real-time. Here, it is noteworthy to mention that “real-time” is a relative concept and, based on the systems/models/applications, it might have different definition or interpretation. In this application, a simulation run with 50 μsec time-steps is considered to be simulated in real-time. As was well-explained in the introduction section of this chapter, hardware development for this research is implemented for a PHIL experiment. This means that the IMU and the test system are developed partially in hardware (NLDL test bed) and the rest is simulated within the RTDS platform.

6.2.1 Real-time small signal stability analysis of a SST via NLDL test bed and through PHIL method

The PHIL experiment shown in Fig. 35 explains the IMU implementation allowing for the small-signal stability of the developed test system to be assessed. The first part of this experiment was to make slight modifications to the model developed in the RTDS platform to enable PHIL experimentation. Basically, these modifications were necessary for communication between hardware and RTDS platform and vice versa. Furthermore, loading the test system under different condition is one of the significant reasons that might push the test system into an unstable region of operation. In an SST, since the output voltage is fixed, changes in the load which it supports will affect the load current. Therefore, in order to assess the test system under
different loading conditions, the load current must be fed back to the RTDS. Moreover, the variable RL load on the LV side of the SST in the RTDS model of test system must be replaced with a controlled current source. This is a fundamental condition for the PHIL experiment. By utilizing a controlled current source (in the RTDS platform) instead of variable RL load, it is possible to employ a variable AC load in hardware and emulate how it affects the simulated model of the test system. Therefore, in the developed PHIL experiment, load current is measured by a probe and converted to digital signal via Analog-to-Digital Converter (ADC). This signal is fed back to RTDS and utilized as a reference for controlled current source in the RTDS model.

The second step in development of the PHIL experiment is hardware development. As is shown in Fig. 35, the final stage of SST in the developed test system is implemented in hardware. To accomplish this, the 3-phase 2-level inverter of the NLDL test bed is modified and utilized. As it was described in 6.1.1, the inverter in the NLDL is a 3-phase inverter; whereas the final stage of the test system is a six-switch, three-leg, single-phase inverter. Therefore, some modifications in the inverter’s LC filter, as well as switching pattern and inverter topology, are required to emulate the three-leg single-phase inverter with 3-phase 2-level inverter[45]. This stage is also available in simulation. In order to be able to conduct a PHIL experiment, the converter should have required nominal power to feed to the variable AC load. This is the main difference between PHIL and other HIL techniques such as Control HIL (CHIL). Therefore, a power amplifier is required to provide power for the inverter. This mission is accomplished by utilizing a 2-level AFE converter in the test bed. The AFE converter is connected to the 3-phase 208 V transformer in the lab, providing 400-V DC to its output terminals. The capacitor in the BTB converters is charged to 400-V DC and reduces DC voltage ripple supplied to the inverter. Moreover, in order to emulate the same DC voltage on the capacitor as is in the RTDS, DC voltage from simulation is sent to the DSP as a reference and this signal is used as DC voltage feedback to the test bed. In addition to the DC voltage signal, two Duty cycles (Ds) are sent to the DSP as D references for the inverter. All three signals sent from RTDS to DSP as references are captured after DAC by scope and are shown in Fig. 42
The DC voltage reference from RTDS is employed in the PI controller to emulate the input DC voltage of the inverter in the test bed. Furthermore, the inverter utilizes D references for switching, enabling the test bed to emulate voltage waveforms at the inverter terminals identical to the RTDS model. For instance output voltages for the no-load test in PLECS model and hardware experiment are shown in Fig. 43 (a) and (b). As is depicted in this figure, the voltage waveforms the simulation and the PHIL experimental waveforms are almost identical. The voltages magnitudes are 120 V RMS and their phase are 180 degree apart from each other.
Fig. 43. Inverter output voltage waveforms for no-load test in (a) PLECS model (b) PHIL experiment
Based on the SST and the PHIL configurations described in Fig. 35, the voltage across load terminals is the difference of the two voltages shown in Fig. 43. Therefore, the magnitude of the voltage waveform across the load in the PHIL experiment is 240 V RMS, and it is illustrated in Fig. 44 along with the inverter input DC voltage.

![Fig. 44. Inverter input (DC) and output (AC across the load) voltages in no-load test](image)

The different stages of the PHIL experiment implementation are as follows:

- Using RTDS for sending the DC voltage reference to the DSP and DSP will control the AFE/DC supply or “controlled voltage source”,
- Using RTDS for sending the D references to the DSP and DSP will control inverter switching accordingly,
- Perturbing the test system with shunt current injection in the source side and chirp signal (different frequencies) in the RTDS platform,
- Measurements are taken place in both hardware and RTDS platform,
• FFT analysis and source impedance/load admittance calculations are accomplished in RTDS platform,
• Further stability study stages such as finding stability criteria, comparing the system’s status to the criteria, and assessing small-signal stability of the system in real-time are completed in RTDS.

6.3 Results for small-signal stability analysis of the developed PHIL experiment

6.3.1 Open-loop test with constant RL load

For the development of above described PHIL experiment, the first stage was to perform an open-loop, no-load test. This step basically compared experimental voltage waveforms with those from the developed model in PLECS and RTDS platforms. The results for this test were discussed comprehensively in 6.2.1. The second step is an open-loop test by connecting the load terminals to the simple RL load. This step has been done by connecting the output terminals of the inverter to the load with \( R = 132 \, \Omega \) and \( L = 1 \, \text{mH} \). The RL load for this experiment is shown in Fig. 45.

![Fig. 45. Constant RL load configuration in the lab](image-url)
Fig. 46 depicts the input DC voltage, output AC voltages, and load current for this experiment. As is depicted, DC voltage is almost 400 (V) with less than 3.7% ripple. The RMS load current is 1.82 (A). The RMS AC voltage across the load is almost 2*114=228 (V).

The PLECS simulation model results for this test are illustrated in Fig. 47. As is depicted in the PLECS results, in steady-state, output DC voltage is almost 400 (V) and the peak value for the AC voltage for each leg is almost 165 (V). After calculation, the RMS voltage across the load is 232 (V), which is close to the measured value from the test. In addition, RMS of the load current from PLECS simulation is 1.83 (A), which is almost identical to the result from conducted experiment.

6.3.2 Closed-loop test with programmable AC load and increment in power

The experiment described in 6.3.1 was an open-loop test. In this work, open-loop means that there is not any feedback from the test bed back to the simulated model in RTDS. An open-
loop test has been conducted to check the test bed settings/configuration by comparing the results with simulation results. As a final step a close-loop test and PHIL experiment will be performed.

![Graphs showing Vdc, Vphase, and Iphase](image)

**Fig. 47. PLECS results for input (DC), output (AC) voltages, and load current for constant RL load test**

Closed-loop tests are actually necessary for PHIL experiments for the reason that there should be feedback from test bed to the simulated model in order to complete a PHIL experiment. This feedback is what makes the test system closed-loop. At this section, the close-loop test that has been done with the NHR 4600 programmable AC load (the introduction to this device along with its specifications are described in the Appendices) and the stability of the test system under different loading condition is investigated in real-time and through a PHIL experiment.

For this test, the PHIL experiment configuration described in Fig. 35 was fully implemented in the Energy Conversion and Integration Thrust Lab. Fig. 48 illustrates different parts of the PHIL experiment in the lab. Different stages of this PHIL experiment development is as follows:

- The RTDS model of the SST runs in real-time,
- The DC voltage and duty cycles are sent to the DSP (through DAC),
- The DSP utilizes above-mentioned signals as references to emulate the last stage of the SST (inverter) in the NLDL test bed,
- Output terminals of the two-level three-leg inverter in the NLDL test bed are connected to the single-phase AC programmable load (NHR 4600),
- The load of the NHR 4600 is incremented and the load current is measured via probe,
- The probe signal (load current) is sent to the RTDS (through ADC) and applies to the controlled-current source,
- Controlled-current source in the RTDS model performs in a way that represents AC programmable load (NHR 4600) is actually in the model and changes. This closes the loop between hardware and simulation and completes the PHIL experiment.

Fig. 48. PHIL experiment configurations in the Energy Conversion and Integration Thrust Lab
In the above-described experiment the programmable AC load is set for a constant power load with unity power factor and the load is changed from 500 (W) to 3 (kW). Fig. 49 depicts scope capture for the DC link voltage in the NLDL test bed along with the load voltage (inverter output) and the current (probe) while the test system is connected to a 500 (W) load. The load current in this condition is 2.357 (A). There is a small ripple (less than 5%) on the DC link voltage as a result of loading the test bed (compare to no-load test that DC ripple was negligible).

Comparing with the no-load test results (Fig. 50) show that the DC voltage ripple is negligible and that there is a small ripple (less than 5%) on the DC link voltage as a result of loading the test bed.
In the next load increment step, the NHR 4600 is set to 1 (kW) and the results are shown in Fig. 51. As is depicted in the scope capture, the RMS load current in this experiment is 4.76 (A) and DC link ripple slightly increased (as expected).

![Fig. 50. Scope capture (DC link voltage and load voltage and current) in no-load test](image)

![Fig. 51. Scope capture while the test bed is connected to 1 (kW) load](image)
The next step is 1500 (W) load and the results are shown in Fig. 52. As can be seen, the RMS load current increased to 7.36 (A) and resulting in an increase in the DC voltage ripple.

![Fig. 52. The PHIL experiment results with 1500 (W) load](image)

The last step in this experiment was to increase the single-phase NHR 4600 AC load to 3 (kW), though it was possible to connect 3 single-phase modules in series or parallel and increase the power to 9 (kW). Furthermore, there are other technical restrictions and single-rack of the NLDL test bed is designed for up to 5 (kW). In this test, DC voltage ripple highly increased (almost 8%) and the voltage and current harmonics are more perceptible. Fig. 53 illustrates the results for the PHIL experiment for this loading condition.

The above-described test was conducted with a step-by-step load change from 500 (W) to 3 (kW), and at each step data from scope was captured and saved. These captures are shown with Fig. 49 - Fig. 53 and they illustrate the actual waveform signals from the hardware (DC voltage link and load voltage and current) which may be utilized for assessment of the simulation results for validation and verification of the PHIL experiment.
Simulation results for all the incremental steps in the load are also captured and illustrated together in Fig. 54. This PHIL experiment was conducted for almost 120 seconds and as can be observed in Fig. 54, the data was collected for 75 seconds. This 75 second period was divided into five 15 seconds parts, where the AC load was changed to 0.5, 0.75, 1, 1.5, and 3 (kW), respectively, for each period. The first graph in Fig. 54 shows the DC voltage link (AFE output) during this experiment. As can be seen, the DC link is held constant at 400 (V) with ripple. The DC voltage ripples are boosted by load increments at the output of the inverter. This fact was showed with the scope captures in Fig. 49 - Fig. 53 as well. The 2nd and 3rd graph illustrate the RMS load current and load voltage transitions for this experiment. The RMS load current values are identical with the values from scope captures. The RMS load voltage remains constant at around 240 (V), since the voltage feedback has been used in the SST to have constant output voltage. The ripple for the voltage is a result of the perturbations with the series voltage injection source. It can be observed that the ripples are higher when the perturbations are closer to 1 (kHz) frequency. The 4th graph shows the magnitude of the return ratio matrix. As it was well-discussed in 4.1, $L_{dd}$ may be used for the small-signal analysis with the unit circle criterion. For stable systems, this value is less than unity. Therefore, the test bed is stable for all the loading conditions in this experiment. The last graph in Fig. 54 depicts the active power transition for this test case.
After validation and verification of the results from test bed and simulation (simulation), it is possible to analyze stability criterion which is calculated in the RTDS platform in real-time and investigate the test bed’s stability during these load changes.

In addition to graph 4 of Fig. 54 that represents unit circle stability criterion ($L_{dc}$), Fig. 55 illustrates the stability criterion based on GNC for the same PHIL experiment. This graph shows the return-ratio matrix in the s-plane and based on (34). GNC considers the phase of the return-ratio in addition to its gain. This provides more precious and less conservative results for the stability analysis. Based on GNC, our system is stable if the return-ratio contour in the s-plane does not encircle the critical point of -1. Therefore, our test bed is stable for all the loading conditions in this PHIL experiment.
In addition to above mentioned figures, the perturbation frequency for the chirp signal has been captured and is illustrated in Fig. 56. This signal has been used for the perturbations in the source side as well as load side (parallel perturbations described in 4.3.2) and based on (35).

6.3.3 Closed-loop test with programmable AC load and DC load in the DC link of the SST

As was described before, the objective in this research is to develop a method/criterion to investigate and analyze small-signal stability of a PEC in different loading conditions in real-
time and to show its usefulness in an SST test system [37]. This goal has been achieved through PHIL experimentation and the test bed was developed and tested in the Energy Conversion and Integration Thrust Lab.

In order to make the test system even more realistic and similar to an actual SST in the FREEDM Distribution Systems and test it for its actual loading condition, one step is added to the PHIL experiment and the results are discussed in this section. In addition to the experiment described in 6.3.2, a DC load is connected to the DC link of the SST (400 V AFE output voltages). This could be an appropriate representation for a battery charging system where an SST charges the battery connected to its DC terminals or any other DC load in the DC terminals of SST. Basically, SST is designed as a bidirectional device which is capable of injecting/withdrawing power to (from) systems connected to its AC and DC terminals. In other words, in nominal operation, the SST should be able to provide power from its DC terminals to the battery (in addition to the AC power provided to loads on its LV terminals) and still remain stable.

For this experiment the PHIL experiment configurations described in 6.3.2 are implemented. The only difference is the connection of a programmable DC load to the DC link of the SST (AFE outputs). The NHR 9200 is utilized as a programmable DC load (in battery discharger mode). This device is shown in Fig. 57 and it is capable of being applied as a DC load (in battery/discharger mode) or a DC source (in source/charger mode). NHR 9200-4960 parameters is shown in Table 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>0-600 VDC</td>
</tr>
<tr>
<td>Current</td>
<td>0-40 ADC</td>
</tr>
<tr>
<td>Sourcing power</td>
<td>0-8 kW</td>
</tr>
<tr>
<td>Sinking power</td>
<td>0-12 kW</td>
</tr>
</tbody>
</table>

81
In this part of the PHIL experiment, a programmable DC load is connected to the DC link of the SST and set at 2 kW in discharge mode. This means that the SST constantly serves 2 kW power to the NHR 9200 from its DC link with the voltage of 400 V in addition to the AC power for the AC load. The configuration of this experiment utilizes devices for this experiment was shown in Fig. 48. In order to study small-signal stability of the SST while it is loaded with AC and DC loads simultaneously, the instantiated test scenario in 6.3.2 is repeated while a 2 kW load is connected to the DC terminals of the SST (in the PHIL experiment output terminals of the AFE) in addition to the AC load. The results are compared to the results of the PHIL experiment in 6.3.2 and it is revealed that the stability of the SST with AC and DC loads is almost the same.
as when the SST only connected to an AC load, the only difference being the voltage ripple in the DC links. Fig. 58 shows the scope captures for this test with no AC load connected to the SST and the only load of the system is the 2 kW DC load connected to the AFE terminals. Comparing this figure to Fig. 53, it is evident that the DC link voltage is slightly higher in this condition. This is as a result of loading the system on its DC links.

![Scopecapture](image)

**Fig. 58. SST output signals (DC link voltage and load voltage and current) with 2 (kW) DC load at its DC terminals in the PHIL experiment**

The PHIL experiment results for the described test scenario with a 1500 W load on the AC output terminals of the SST and a 2 kW load on the DC terminals is illustrated in Fig. 59. As it is evident from comparing the figures, DC voltage ripple here is higher than the experiment without a DC load, whereas the other parameters (i.e. stability criterion) stay almost identical.
In the next (and last) step of this test scenario, the AC power in the output terminals is increased to 3 (kW). The results for this part (shown in Fig. 60) are also similar to the test case without DC load, as anticipated. In other words, besides the slight increase in the DC voltage (which was seen in a variety of loading conditions), none of the other characteristics/parameters of the SST change. The stability criterion for the SST with these three different AC loading conditions of no-load, half-loaded, and fully-loaded with and without DC load in the DC terminals is identical. Therefore, it can be concluded that for any loading condition, small-signal stability of the SST, and in general, PECs, is not affected by DC load (provided that its power is in the nominal range), as is expected. Although loading a PEC with a large DC load may jeopardize small signal stability of the systems, the proposed small-signal stability criterion is not supposed to change by changes in the DC link of the PECs (if there are any changes in the DC link of the PECs).

**Fig. 59. The PHIL experiment scope captures with 1500 (W) load in the AC terminals and 2 (kW) load in the DC terminals of the SST**
Therefore, it is logical to assume that the stability criterion for the test bed in this loading condition (AC and DC loads at the same time) is identical to the test system described in 6.3.2 and shown in Fig. 54. Furthermore, the generalized Nyquist contour associated with this PHIL experiment is almost identical to the one was illustrated in Fig. 55.
CHAPTER 7
CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORKS

7.1 Conclusion

This study has proposed a novel stability assessment technique for the Peds. The proposed technique essentially investigates the small-signal stability of distribution systems in real-time. This technique was based on the d–q impedance measurement theory with the Perturb-and-Observe algorithm (in the operational stage as opposed to design stage) and Generalized Nyquist Criterion. Furthermore, in this research it was proven that perturbing the systems in a range of frequencies can capture some parts of the system’s nonlinearities, even when utilizing the linearized model of the system. In order to perturb the system in a range of frequencies and still be able to perform and operate in real-time, chirp signal was utilized for source and load perturbations. On the other hand, in order to study the small-signal stability of the systems with the impedance measurement technique in real-time, source and load impedances have to be captured simultaneously. To accomplish this, it was proposed that parallel perturbations be made in the source and load sides of the PECs. In addition it was proven that for the stiff interconnected source-load systems (PECs), perturbations made with a shunt current source mainly affect the source side, whereas perturbations made with a series voltage source result in perturbing the load side of the system. Therefore, for parallel perturbations, a chirp shunt current injection source was implemented to perturb the source side of the system and a chirp series voltage injection source was utilized to perturb, and capture impedance data of, the load. Furthermore, it was shown that perturbations with a magnitude of 0.5% of fundamental voltage/current signals sufficiently perturbed the system to determine stability, but did not interfere with the system’s normal operation by adding extra harmonics.

Generally with this method, the PEC must be persistently perturbed so that by utilizing the responses of the perturbations, \( Z_{dqs} \) and \( Y_{dql} \), the return-ratio matrix of the system can be calculated. Moreover, in this method, FFTs were utilized to transfer time-domain data to frequency-domain data. After obtaining magnitude and phase angle of the components of the return-ratio matrix, the small-signal stability of the PECs could be assessed based on GNC. Furthermore, it was shown that it is possible to use the magnitudes of the return-ratio matrix’s
components to monitor the relative stability of the systems in real-time, based on the unit circuit
criterion.

In this study it was shown that by utilizing this method, it is possible to track the stability
of a system while in operation. In other words, this method allows for real-time stability
assessment to be made in a system, even while applied data is being extracted from said real-
time simulation and/or real system. To demonstrate this, the proposed technique was
implemented for a test system built in the RTDS platform, and small-signal stability of a PEDS
with 2 SSTs was assessed in real-time. In addition to this, the interaction between SSTs was
studied for the case when only one SST is unstable, yet causes the rest of the distribution system
to lose stability. Basically, in this condition, the unstable SST causes instability in the
distribution system, which is viewed as a source by the other SST, thus jeopardizing its stability
condition.

As a final demonstration of the technique for hardware development and experimental
implementation, the small-signal stability of a SST was assessed in real-time. For this
experiment, an IMU was developed partially in the RSCAD simulation software platform and
partially in an actual hardware test bed (via the PHIL method). Subsequently, stability of a SST
was investigated through the PHIL experiment by implementing the final inverter stage of the
SST into the NLDL test bed and loading the SST with the NHR 4600 programmable AC load.
The magnitude of the AC load connected to the SST was changed and the stability criterion of
the test system was analyzed, along with the voltages/currents/power waveforms. In a separate
test scenario, a 2 kW DC load was connected to the DC terminals of the AFE output of the SST
while it was connected to the programmable AC load, thus demonstrating the battery charging
capability of the SST and investigating the small-signal stability of the system for this loading
condition in real-time.

7.2 Recommendations for future works

For future studies, we propose assessing small-signal stability by considering the
nonlinearities of the systems. The PECs illustrate nonlinearities caused by nonlinear behavior of
the converters and switching, and thus it would be highly beneficial to address these
nonlinearities during small-signal stability studies of the system. Some proposed methods to take
the systems’ nonlinearities into account are utilizing more mathematically sophisticated techniques, such as the Volterra theorem or complexity theory.

Additionally, the assessment of small-signal stability for larger distribution systems, such as a PEDS with 200+ nodes, and the expansion of the proposed technique for the larger distribution systems are potential areas of research that would play a prominent role in the prospect of contemporary PEDS, as could the improvement of the proposed technique and criterion. An example of this could be the investigation of the developed method/criterion for a variation of the “source side” of the PEC as a replacement for load variation. Although the effect of variations in the source on the stability of the system has been addressed in 5.4.2, and it was shown that an unstable distribution system may affect the stability of the PECs in the system and the proposed stability criterion in the PEC can distinguish instability of the PEDS, this effect needs to be studied separately and comprehensively by additional research. The results of this research could then be utilized to improve the capabilities of the proposed method for addressing the variation of the PEDS, such as changes in the system’s configuration, voltage/frequency variation, and load curtailment in power systems.
APPENDIX A

“NHR 4600 AC LOAD”

A.1. Introduction

The NHR 4600 AC Load in the Energy Conversion and Thrust Lab (Fig. 61) is comprised from three individual modules that each module is a single-phase programmable AC load. Therefore this device has the capability to operate in different 3-phase configurations (delta and star) as well as any other single phase configuration (three modules in series or parallel). Introduction to each module of this device along with its specifications are described in following.

4600 Series AC Electronic Loads are intended for applications that require the entire range of non-linear loading

- Programmable power-factor & crest-factor
- 3KW/30A and 6KW/60A power ratings
- Built-in, high-accuracy measurements
- Graphical user interface and LabVIEWtm driver

4600 Series AC Electronic Loads are intended for applications that require the entire range of non-linear loading to thoroughly test AC-output power conversion products such as uninterruptible power supplies (UPS) and inverters. The benefits of such a wide range of loading control is to assure product performance under every possible "real world" operating condition.

Fig. 61. NHR 4600 (programmable 3-phase) AC load picture in the Energy Conversion and Integration Thrust Lab
A.1.1. Non-Linear Loading
The advantage of testing with a programmable, non-linear (i.e., any power-factor and crest-factor) load are substantial. The most significant being the ability to rapidly test products at every possible loading condition that could ever be encountered in the field. The other major benefit is the ability to instantly switch over to a different set of loading conditions as product needs dictate. With such versatility, a higher level of product quality is assured and manufacturing test throughput is increased.

A.1.2. Broad Operating Envelope
In order to cover the most common UPSs and inverters, the 4600 Series is offered in two power ranges, 3000W and 6000W. Higher power levels can be achieved by utilizing additional units in parallel. All units operate from 50 to 350VAC and in several emulation modes such as Constant-Current, Voltage, Resistance, and Power as well as Short-Circuit.

A.1.3. A "One Box" Test Solution
With a PC controller, everything needed to test most AC-output products is contained within the 4600 Series instruments. In addition to the flexible load control, twelve high-accuracy measurements include voltage, current, peak-current, frequency, crest-factor, power-factor, and true power. Even the real-time voltage, current and power waveforms are displayed on the PC soft-panel. This ability to make all measurements internally eliminates multiple, external measurement instruments plus associated signal matrixing and interconnect wiring. In this manner the 4600 Series provides for a more compact, less costly and considerably faster test solution [NH Research].

A.2. Specifications [NH Research]

A.2.1. Ratings
Power: 3000W 0 - 37° C, 2400W 38 - 50° C
Max. Peak power: 13kW (up to 20% duty cycle)
Current: 30A rms.
  Max. Peak current: 90A
Voltage: 50 to 350V rms.
   Max. Peak voltage: 500V
Frequency: 45 to 440Hz

**A.2.2. Programmable Features**

**Constant Current Mode**
   Range: 0 to 30A rms.
   Accuracy: 0.2% of full scale
   Resolution: 0.05% of full scale

**Constant Voltage Mode**
   Range: 50 to 350V rms.
   Accuracy: 0.2% of full scale
   Resolution: 0.05% of full scale

**Constant Resistance Mode**
   Range: 2.5 to 100Ω, 100 to 1000Ω
   Accuracy: 1% of full scale, 5% of full scale
   Resolution: 0.05% of full scale

**Constant Power Mode**
   Range: 3000W 0 - 37° C, 2400W 38 - 50° C
   Accuracy: 0.5% of full scale
   Resolution: 0.05% of full scale

**Crest factor**
   Range: $\sqrt{2}$ to 4.0, limited to 90A peak
   Accuracy: 1% of full scale
   Resolution: 0.05% of full scale

**Power factor**
Range: 0 to 1 lead or lag limited by Crest factor settings

Accuracy: 1% of full scale

Resolution: 0.05% of full scale

Short circuit Mode
Max. Surge current: 300A peak, up to 50msec

Max. Continuous current: 30A rms.

Max. Voltage drop: 2.5Vr.m.s.

Maximum Set Resistance = 1 / (Frequency * 1.3e-5)

Minimum Set Current = Voltage / Maximum Set Resistance

A.2.3. Read-back Instrumentation

Frequency
Range: 45 to 440Hz

Accuracy: 0.1% of full scale

Resolution: 0.01% of full scale

Voltage
Range: 50 to 350V rms.

Accuracy: 0.1% of full scale

Resolution: 0.01% of full scale

Peak Voltage
Range: 50 to 500V

Accuracy: 0.5% of full scale

Resolution: 0.01% of full scale

Current
Range: 0 to 30A rms.

Accuracy: 0.2% of full scale
Resolution: 0.01% of full scale

Peak Current
  Range: 0 to 90A
  Accuracy: 0.5% of full scale
  Resolution: 0.01% of full scale

Crest factor
  Range: $\sqrt{2}$ to 4.0
  Accuracy: 0.5% of full scale
  Resolution: 0.01% of full scale

Apparent Power
  Range: 0 to 10,500VA
  Accuracy: 0.3% of full scale
  Resolution: 0.01% of full scale

True Power
  Range: 0 to 10,500W
  Accuracy: From 90 - 130VAC, 47 - 63Hz, 0.2% reading + 0.03% full scale.
  Resolution: 0.01% of full scale

Peak Power
  Range: 0 to 45,000W
  Accuracy: 1% of full scale
  Resolution: 0.01% of full scale

Reactive Power
  Range: 0 to 10,500VA
  Accuracy: 0.3% of full scale
  Resolution: 0.01% of full scale
Power factor
    Range: 0 to 1
    Accuracy: 0.5% of full scale
    Resolution: 0.01% of full scale

Resistance
    Range: 2.5 to 100Ω, 100 to 1000Ω
    Accuracy: 1% of full scale, 5% of full scale
    Resolution: 0.01% of full scale

A.2.4. Protection

Over Current
    Limited by input Circuit Breaker
    Limited to Set Maximum Current Limit in software

Over Voltage
    Output protected for voltage transients in hardware

Over Power
    Power limited at maximum average and peak rated power in hardware
    Limited to Set Maximum Power Limit in software

Over Temperature
    Monitors heat sink temperature in hardware

A.2.5. Supplemental Characteristics

Size:
    8.75”H x 16.88”W x 25”D, 40 lbs.

Remote Sensing:
    Max. 2V drop between sense and load lines

Isolation:
1000V between input and chassis ground

Operating temperature:

3000W 0 - 37° C, 2400W 39 - 50° C

Control power input:

Ordered from factory as either 115VAC ± 10%, 47 to 63Hz, 1.4A Max.

OR 230VAC ± 10%, 47 to 63Hz, 0.7A Max.

All specifications apply for 23oC ± 5oC
REFERENCES


BIOGRAPHICAL SKETCH

Mohamadamin Salmani was born in Tehran, Iran. He received his BSc degree in 2006 and MSc in 2009 in Power Electrical Engineering from K. N. Toosi University of Technology Tehran/Iran. He has worked in Iran Power Plant Projects Management (MAPNA) Company from 2009 till 2011. He is currently pursuing a Ph.D. degree from Florida State University under supervision of Dr. Chris S. Edrington.

He has worked at Florida State University’s Center for Advanced Power Systems (CAPS) since 2011. During this period he has worked as a research assistant for NSF Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Center. He is also part of “Verification of FREEDM System Robustness and Control” research group in the FREEDM Systems Center. Furthermore, during this period, he has been actively involved in FREEDM Centre’s extracurricular activities such as, FSU leader of the “Summer Scholar Program” for 2013 and 2014, leader of the FREEDM Systems Center Student Leadership Council (SLC) at FSU and FSU Student Representative in 2013 and 2014.

His research interests include Power Electronics and Drives, Power Systems, Small-Signal Stability Assessment, Renewable Energy Integration, Energy Management Systems and Distributed Generations. He has published several papers and disclosed a provisional patent application in these research areas.

PUBLICATIONS LIST

- CONFERENCES


**JOURNALS**


- PATENT LIST